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February 1992

INTEGRATED CONTROL AND HEALTH MONITORING

ASSESSMENT OF TECHNOLOGY READINESS AND DEVELOPMENT COSTS

ORBIT TRANSFER ROCKET ENGINE TECHNOLOGY PROGRAM TASK E.7

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Propulsion Division

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This final report describes the work performed under Task Order No. E.7 of the Orbit Transfer Rocket Engine Technology contract.

The NASA technical monitor was Mr. Marc Millis, M/S 500-220, with support from Mr. Mike Binder, M/S 500-220.

16. Abstract

The objectives of this task were to : (1) estimate the technology readiness of an integrated control and health monitoring (ICHM) system for the Aerojet 7500-lbF OTV engine preliminary design assuming space-based operations; and (2) estimate the remaining cost to advance this technology to a NASA defined "Readiness Level 6" by 1996 wherein the technology has been demonstrated with a system validation model in a simulated environment.

The work was accomplished through the conduct of four subtasks. In Subtask I the minimally required functions for the control and monitoring system were specified. The elements required to perform these functions were specified in Subtask II. In Subtask III the technology readiness level of each element was assessed. Finally, in Subtask IV the development cost and schedule requirements were estimated for bringing each element to Readiness Level 6.

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1.0 EXECUTIVE SUMMARY

A preliminary design and cost estimate for the development of an Integrated Control and Health Monitoring (ICHM) system for the Aerojet 7500 lbF OTV engine was completed. The system would provide real-time control and diagnostics during all phases of engine operation, including Pre-Start, Pump Chilldown, Tank Head Idle, Pumped Idle, Main Stage Operation, and Shutdown. The system would support space-based operations of the engine, which is required to be fully reusable, without ground maintenance, for 20 complete missions consisting of 100 engine starts and 4 hours of hot-fire duration. The engine operational life must be 100 complete missions, with 500 engine starts and 20 hours of firing duration.

The minimum required functionality of the ICHM system was defined as part of this study. The ICHM would be responsible for controlling all engine operations, providing real-time safety and diagnostic monitoring of all engine components, providing data communications between the engine and the vehicle avionics, and providing data acquisition and storage for all engine measurements.

The devices or elements of the ICHM required to provide these functions were then identified and preliminary specifications for each were developed. The elements of the ICHM fell into one of fifteen categories: A) Control Computer Unit; B) Monitoring Computer Unit; C) Triple Channel 1553B Module; D) General Output Electronics; E) Low Speed Input Electronics; F) High Speed Input Electronics; G) Interchannel Communications; H) Control Software; I) Monitoring Software; J) Power Supply Electronics; K) Mass Data Storage; L) Harnesses; M) Distributed Signal Conditioners; N) Control Effectors; and O) Sensors.

The current state-of-the-art was compared with the preliminary specifications of each of the ICHM elements. The NASA seven-level rating scale was used. Elements of the electronics hardware were estimated at current technical readiness levels 4 and 5, control and diagnostic software at levels 2 and 3, control effectors at levels 4 and 5, and sensors and distributed signal conditioners anywhere from level 1 to 7. The overall system was rated at a composite readiness level of 4.

The cost and time necessary to advance all the elements of the required ICHM system to a minimum of technical readiness level 6 were estimated. The entire effort was estimated to cost $33.8M, and require approximately five years. Figure 1 summarizes the cost and schedule estimates which were developed.

2.0 INTRODUCTION

The objectives of this task were to: (1) estimate the technology readiness of an integrated control and health monitoring (ICHM) system for the Aerojet 7500-lbF OTV engine preliminary design assuming space-based operations; (2) estimate the remaining cost to advance this technology to a NASA defined "Readiness Level 6" by 1996 wherein technology has been demonstrated with a system validation model in a simulated environment; and (3) publish this information as a NASA Contractor Report. All levels of the ICHM system were addressed to approximately equal levels of detail, including sensors, signal processing, engine control modeling, health assessment algorithms, controllers, vehicle interfaces, valves, and actuators. The focus of the effort was on minimally required ICHM functions; however, some advanced functions were addressed.

The task objectives were accomplished through the conduct of four subtasks. These were defined as follows.

- Subtask I - Specify Minimum OTV Engine ICHM Functions

Based on the OTV engine preliminary design, the minimally required functions that the ICHM system must perform to operate the engine in space were specified. Control, monitoring and interface requirements were addressed in detail.

- Subtask II - Identify Elements of OTV Engine ICHM System

Based on the OTV engine preliminary design and the results of Subtask I, a comprehensive list of the elements comprising the ICHM system was prepared. These elements included sensors, signal conditioning hardware and software, distributed processors, control processors, interfaces, actuators, math models, diagnostic software, control software, data compression, data storage, redundancy, and self-test techniques.

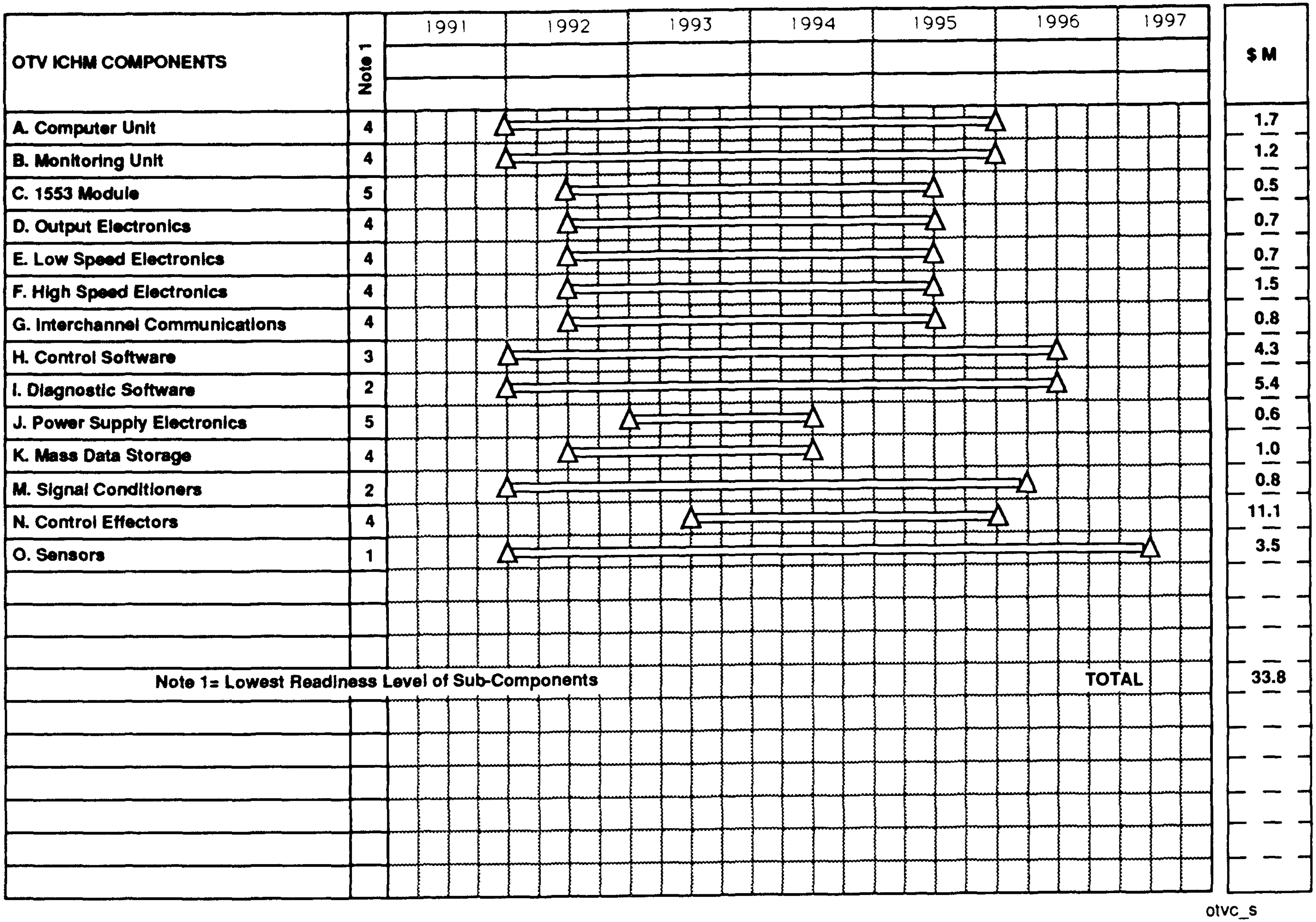


Figure 1. OTV Schedule to Bring ICHM Components to Tech Readiness Level 6

- o Subtask III - Estimate Technology Readiness for Minimal System

The current "technology readiness" was estimated for each of the ICHM elements defined in Subtask II. The NASA provided, seven-level rating scale was used. The rating scale is discussed in Section 5.0 of this report.

- o Subtask IV - Estimate Remaining Development Cost for Minimal System

Estimates were prepared of the remaining cost and schedule necessary to advance each ICHM element (from Subtask II) to NASA technology readiness Level 6 by 1996. This is defined as a "system validation model demonstrated in a simulated environment."

2.1 ENGINE DESCRIPTION

The Aerojet 7500-lbF OTV engine design uses a unique form of the expander cycle developed for high-performance, turbopump-fed liquid oxygen/liquid hydrogen fueled engines. It is a dual expander cycle which makes use of both hydrogen and oxygen as working fluids to drive their respective turbopumps. Using both hydrogen and oxygen as *working fluids* allows the dual expander cycle to deliver higher combustion chamber pressures at lower fluid temperatures than a conventional expander cycle. The engine mechanical layout is shown in Figures 2 and 3. The engine schematic is shown in Figure 4.

The hydrogen fuel is used as the regenerative coolant for the combustion chamber jacket where it acquires energy to drive the hydrogen turbopump. Additional energy is acquired by ducting the hydrogen through baffles in the main combustion chamber. The oxygen, heated in the O_2/H_2 heat exchanger, acquires further energy in the oxygen-cooled nozzle extension and drives the oxygen turbopump.

Engine operation is controlled by the 11 valves shown on the schematic, plus two igniter solenoid valves. These valves, their function, and sensor data source are shown in Table I. All valve sequencing and positioning are controlled by an electronic engine controller and by line pressure actuation.

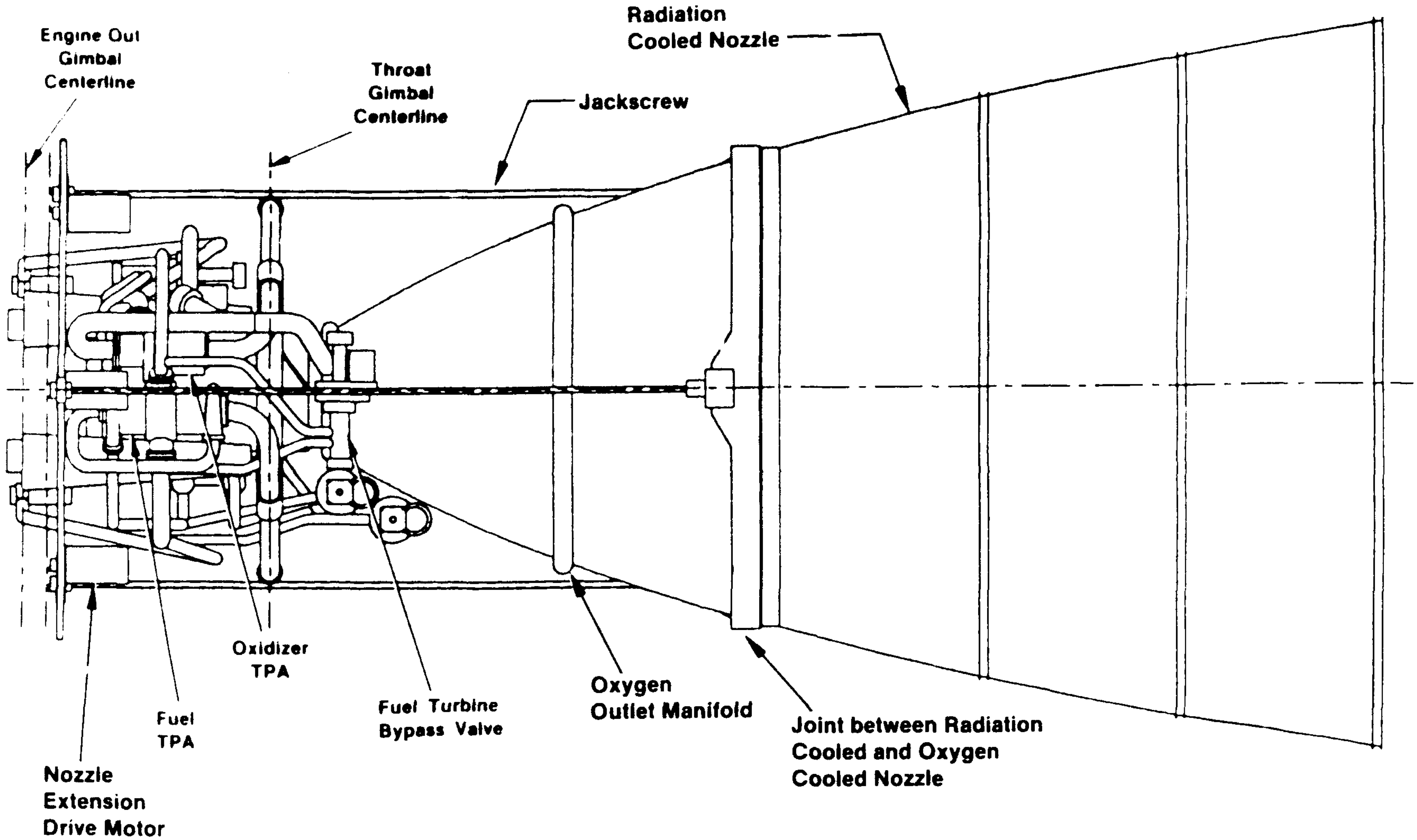
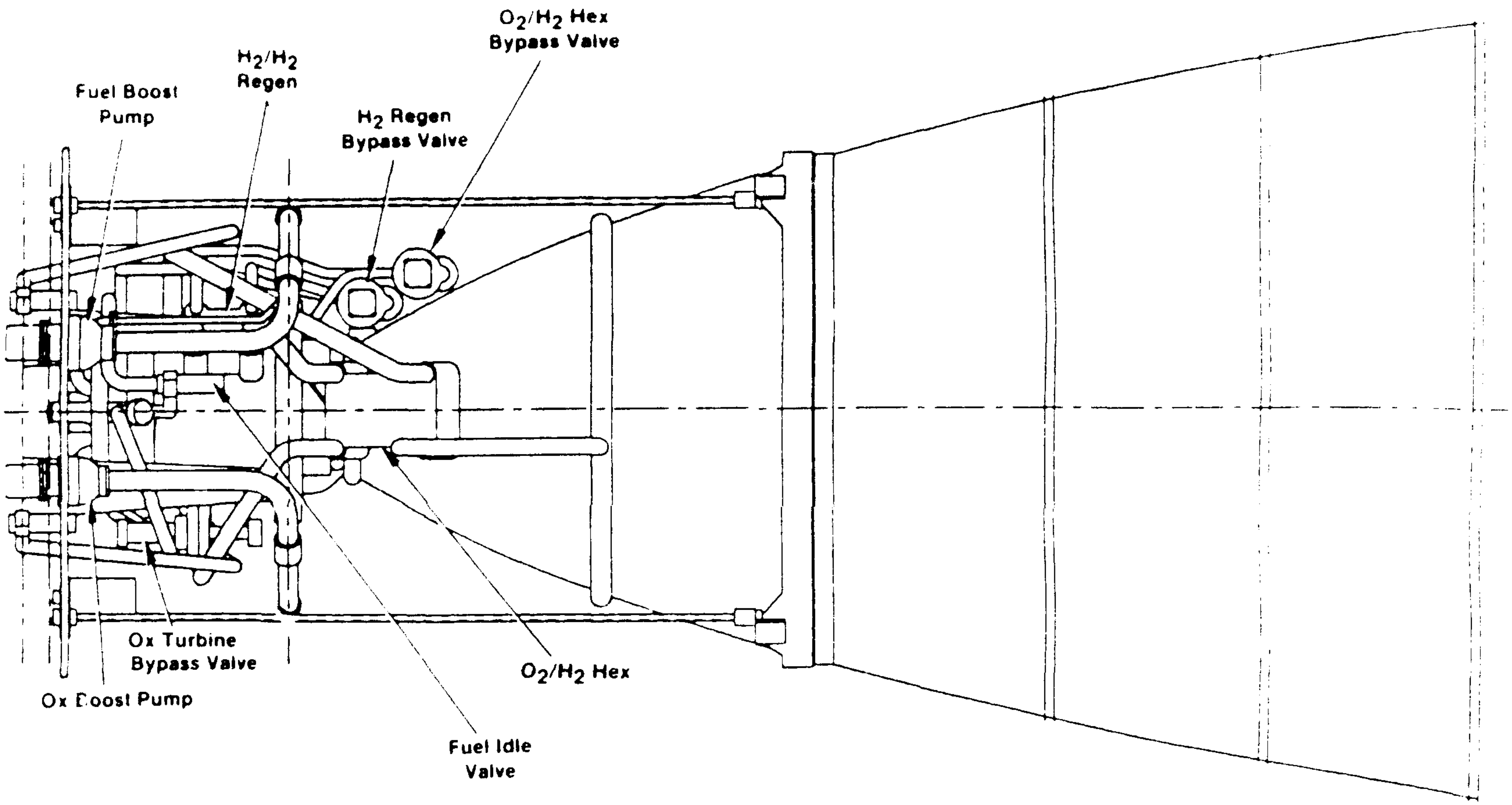


Figure 2. OTV Engine Preliminary Design Component Locations View A



Propellant Inlet Side

Figure 3. OTV Engine Preliminary Design-Component Locations View B

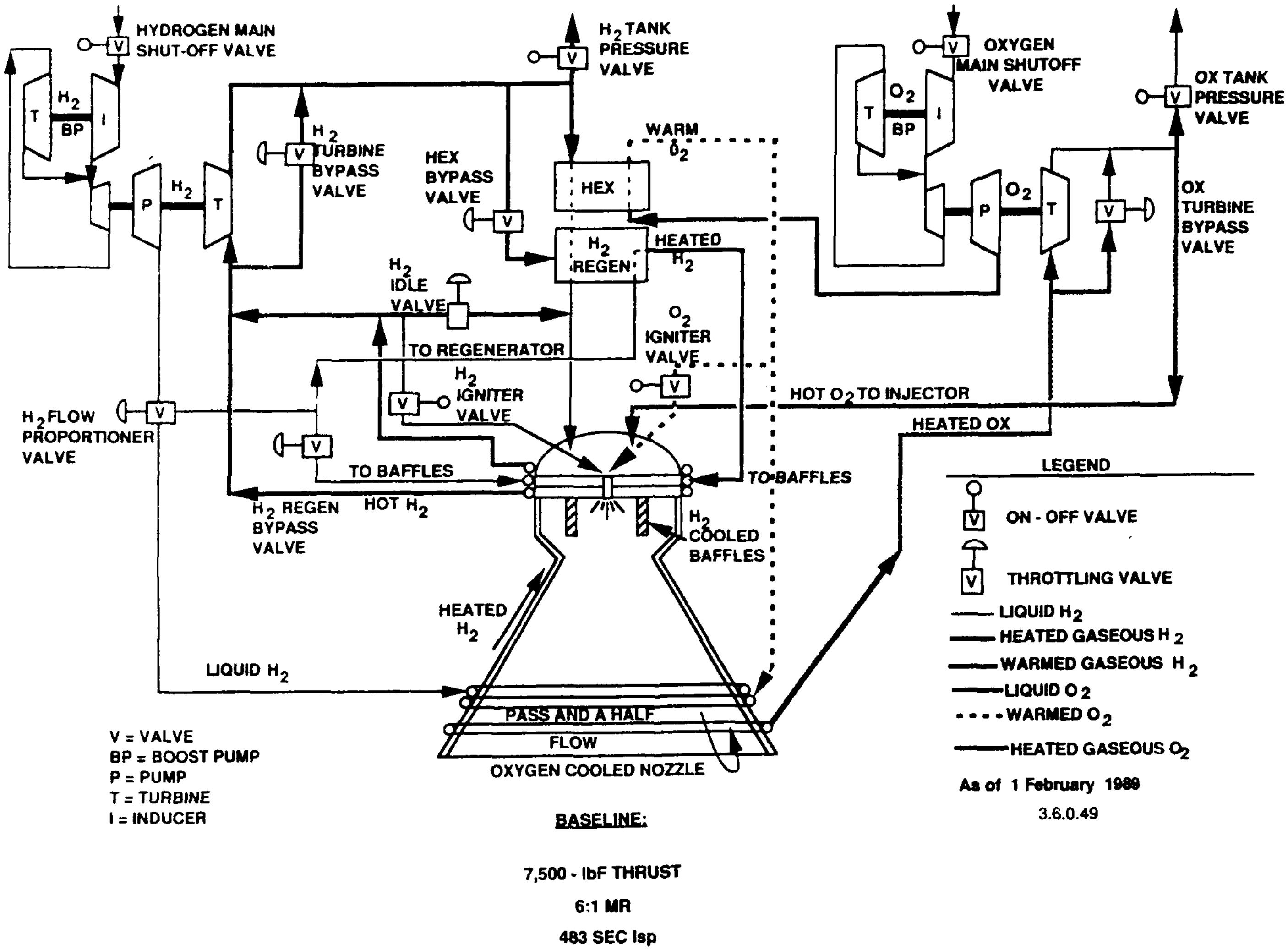


Figure 4. OTV Engine Dual Expander Cycle Schematic

TABLE I

OTV-ENGINE VALVES AND SENSORS FOR ENGINE CONTROL

Valve Name	Abbreviation	Control Function	Primary Sensor Data Source
Hydrogen Turbine Bypass	HTBV	Mixture Ratio	Hydrogen & Oxygen Flowmeters, TPA Speeds, Chamber Pressure, OTBV Position
Oxygen Turbine Bypass	OTBV	Thrust	Oxygen & Hydrogen Flowmeters, TPA Speeds, Chamber Pressure
Heat Exchanger Bypass	HEBV	Oxygen Max. Temp.	Oxygen Turbine Inlet Temperature
Hydrogen Regenerator Bypass	HRBV	Hydrogen Max. temp., Thrust Supplement	Baffle Outlet Temperature, Chamber Pressure
Hydrogen Idle	HIV	*Idle Mode Start*	*Flowmeter Data*, Chamber Pressure
Hydrogen Proportioner	HPV	Hydrogen Split (Regen/Baffle)	Baffle & Chamber Outlet Temperatures
Hydrogen Main Shutoff	HMSV	Propellant Isolation	Commanded by OTV Pilot (Engine Start, Stop) or Engine ICHM System
Oxygen Main Shutoff	OMSV	Propellant Isolation	Commanded by OTV Pilot (Engine Start, Stop), or Engine ICHM System
Hydrogen Igniter Control	HICV	Engine Start	Chamber Pressure
Oxygen Igniter Control	OICV	Engine Start	Chamber Pressure
Oxygen Tank Pressurization	OTPV	Tank Pressurization	Tank Pressure, TPA Speed
Hydrogen Tank Pressurization	HTPV	Tank Pressurization	Tank Pressure, TPA Speed

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2.2 ENGINE OPERATION AND CONTROL

The engine operational sequence is described in Table II. It consists of the following primary operating modes:

- o Pre-Start
- o Pump Chilldown
- o Tank Head Idle
- o Pumped Idle
- o Main Stage
- o Shutdown

The operating sequence from tank head idle through shutdown is illustrated in Figure 5. The ICHM system is operational throughout this sequence. The component states throughout the operating sequence are shown in Table III. The stages in the operating sequence are defined as follows.

- o Pre-Start Operations

Engine Positioning - Aerobrake doors opened, radiation-cooled nozzle extended, gimbal operated to position thrust vector through estimated center of mass.

Engine Status Check - ICHM system powered up, controller and valve functional checks, sensor calibration and built-in test, vehicle preparations complete for start, engine valves positioned for start.

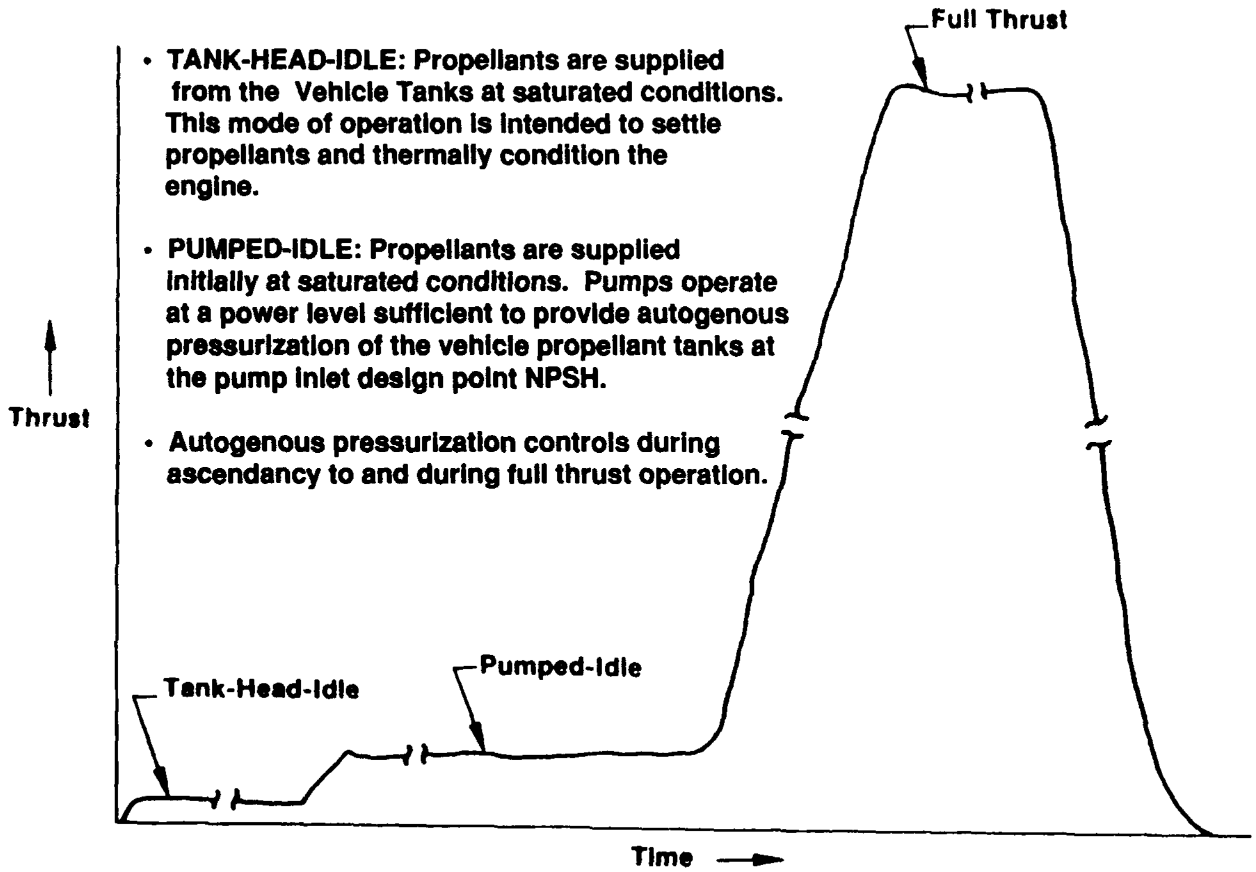
Turbopump Chilldown - The turbopumps must be cooled to the same temperature as the propellants to avoid flash evaporation in the pump section with subsequent damaging pump cavitation. In the baseline engine cycle, this is done by dump cooling through the pumps with propellant from the tanks. The greater rotating mass of the hydrogen TPA, plus its lower operating temperature, will require a longer chilldown time than the oxygen system. The oxygen pump is chilled down first by dumping oxygen until the desired pump temperature is reached. The oxygen valve is closed and the hydrogen shut-off valve is opened to chill the hydrogen pump. When the hydrogen pump chilldown is completed, the igniter is turned on, the igniter valves opened, and the oxygen main shutoff valve is opened

TABLE II

ENGINE OPERATION SEQUENCE

TABLE ENTRY NUMBER	OPERATION	ACTIONS/STATE
00	NOZZLE EXTENSION RETRACTION	28V DC MOTOR DRIVEN BALL SCREWS TERMINATED BY LIMIT SWITCHES/TORQUE
0	ENGINE GIMBAL	28V DC DRIVEN ACTUATORS (2)
1	CONFIGURE ENGINE FOR CHILLDOWN	CLOSE FUEL AND OX TURBINE BYPASS, OPEN FUEL REGEN BYPASS VALVE, CLOSE FUEL IDLE VALVE, OPEN OX IGNITER VALVE (IGNITION OFF)
2	CHILLDOWN 0_2 TPA	OPEN OX MAIN VALVE (GASEOUS 02 FLOWS THROUGH THE TPA PUMP, HEX, OX COOLED NOZZLE, TPA TURBINE, INJECTOR, AND OUT THE ENGINE NOZZLE), CLOSE OX MAIN VALVE ON REACHING TEMP, CLOSE OX IGNITER VALVE
3	CHILLDOWN H_2 TPA	OPEN H_2 IGNITER VALVE, OPEN FUEL MAIN VALVE (GASEOUS HYDROGEN FLOWS THROUGH THE LH_2 PUMP, CHAMBER AND BAFFLE CIRCUITS, H_2 TPA TURBINE, REGENERATOR, INJECTOR, AND OUT THE ENGINE NOZZLE.) CLOSE FUEL MAIN VALVE ON REACHING THE TPA OPERATING TEMPERATURE, CLOSE H_2 IGNITER VALVE
4	LIGHTOFF	OPEN OX MAIN VALVE, OPEN FUEL MAIN VALVE, OPEN IGNITER VALVES ACTUATE IGNITERS
5	TANK HEAD IDLE	MODULATE FUEL IDLE VALVE FOR MIXTURE RATIO CONTROL, HYDROGEN PROPORTIONED VALVE FOR CHAMBER/ BAFFLE TEMPERATURE CONTROL, ENGINE TEMPERATURES STABILIZED, COMBUSTION SMOOTH, IGNITERS OFF
6	PUMPED IDLE MODE	MODULATE TURBINE BYPASS VALVES TOWARDS CLOSED, CLOSE FUEL IDLE VALVE, CLOSE REGEN BYPASS VALVE, CLOSE HEX BYPASS VALVE UNTIL OX TURBINE IS 400°F. ACCELERATE TPA'S TO PUMPED IDLE SPEED, HOLD BY MODULATING TURBINE BYPASS VALVE, STABILIZE ENGINE TEMPERATURE.

		EVALUATE HEALTH MONITOR SYSTEM READINGS. BEGIN MAIN TANK AUTOGENOUS PRESSURIZATION
7	NORMAL OPERATING RANGE	COMMAND ENGINE THRUST. OX TURBINE BYPASS VALVE MOVES TO THRUST SCHEDULE SETTING WITH FUEL TURBINE BYPASS VALVE FOLLOWING REGEN BYPASS VALVE MOVES TOWARDS CLOSED POSITION TO MEET THRUST REQUIREMENT HEX BYPASS VALVE MODULATES TO KEEP OX TURBINE INLET TEMP AT 400°F. HYDROGEN PROPORTIONER VALVE ADJUSTS TO KEEP THROAT TEMPERATURE WITHIN LIMITS. MIXTURE RATIO TRIMMED BY H_2 TURBINE BYPASS VALVE.
8	OVERTHRUST	COMMAND ENGINE THRUST WITH OVERRIDE ON TURBINE BYPASS CONTROL LOWER RANGE. INCREASE MIXTURE RATIO TO 7. OX TURBINE BYPASS MOVES TO THRUST SCHEDULE SETTING WITH OTHER VALVES FOLLOWING AS IN NORMAL OPERATION. HEALTH MONITOR SYSTEM WILL REDUCE THRUST ON A TREND TOWARDS UNSAFE TEMPERATURE. THRUST MAY FLUCTUATE AS CONTROLLER MAINTAINS MIXTURE RATIO WITH A TURBINE BYPASS VALVE AT ZERO BYPASS
9	NORMAL SHUTDOWN	SHUTDOWN COMMAND INITIATES THROTTLE DOWN TO PUMPED IDLE RANGE. AT IDLE TPA SPEEDS, THE FUEL AND OXYGEN MAIN VALVES ARE CLOSED, TURBINE BYPASS VALVES COMMANDED FULL BYPASS, REGEN BYPASS AND HEX BYPASS VALVES TO FULL BYPASS, IDLE VALVE FULL OPEN. IGNITER VALVES OPEN, IGNITION ON. RESIDUAL PROPELLANT IS VENTED TO SPACE THROUGH THE NOZZLE. ENGINE CENTERED
10	NORMAL GIMBAL	28V DC GIMBAL ACTUATORS ARE ACTIVATED PER CONTROLLER INSTRUCTIONS AT ANY TIME DURING ENGINE OPERATION
11	OPERATIONAL STORAGE	THERMOSTATICALLY CONTROLLED HEATER POWER FOR VALVES AND SENSOR ELECTRONICS AND DC MOTORS, THERMAL CONTROL POWER TO ICHM SYSTEM, ENGINE CENTERED, NOZZLE EXTENSION RETRACTED



Engine Start to Full Thrust is to be Accomplished Using Tank-Head-Idle and Pumped-Idle Operating Modes as Shown Above

Figure 5. OTV Engine Start Cycle

TABLE III

COMPONENT STATE DURING ENGINE OPERATION

COMPONENT	PRE START	H_2 PUMP CHILLDOWN	0_2 PUMP CHILLDOWN	TANK HEAD START	TANK HEAD IDLE	PUMPED IDLE	THROTTLE RANGE	RATED THRUST	SHUTDOWN
HYDROGEN MAIN SHUTOFF	CLOSED	OPEN	CLOSED	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSED
OXYGEN MAIN SHUTOFF	CLOSED	CLOSED	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSED
OX TURBINE BYPASS	0% BP	0% BP	0% BP	100% BP	100% BP	MODULATES	MODULATES	10% BP	100% BP
HYDROGEN TURBINE BYPASS	0% BP	0% BP	0% BP	100% BP	100% BP	MODULATES	MODULATES	10% BP	100% BP
HEAT EXCHANGER BYPASS	100% BP	100% BP	100% BP	25% BP	MODULATES	MODULATES	MODULATES	MODULATES	100% BP
REGENERATOR BYPASS	100% BP	100% BP	100% BP	25% BP	MODULATES	MODULATES	MODULATES	10% BP	100% BP
HYDROGEN IDLE	OPEN	OPEN	OPEN	OPEN	MODULATES	CLOSED	CLOSED	CLOSED	OPEN
HYDROGEN IGNITER	CLOSED	OPEN	CLOSED	OPEN	OPEN	CLOSED	CLOSED	CLOSED	OPEN
OXYGEN IGNITER	CLOSED	CLOSED	OPEN	OPEN	OPEN	CLOSED	CLOSED	CLOSED	OPEN
HYDROGEN PROPORTIONER VALVE	NEUTRAL	NEUTRAL	NEUTRAL	NEUTRAL	MODULATES	MODULATES	MODULATES	MODULATES	NEUTRAL
HYDROGEN TANK PRESS.	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CYCLES	CYCLES	CYCLES	CLOSED
OXYGEN TANK PRESS	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	CYCLES	CYCLES	CYCLES	CLOSED
IGNITERS	OFF	OFF	OFF	ON	ON*	OFF	OFF	OFF	ON*
HYDROGEN TPA	STOPPED	WINDMILL	STOPPED	WINDMILL	WINDMILL	PUMP OUTPUT	OUTPUT	RATED OUTPUT	GOES TO STOP
OXYGEN TPA	STOPPED	STOPPED	WINDMILL	WINDMILL	WINDMILL	PUMP OUTPUT	OUTPUT	RATED OUTPUT	GOES TO STOP

* TO PREVENT POPPING OR UNCONTROLLED IGNITION

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to provide the tank head start. During chilldown operation, the low-pressure boost pumps will spin up and the high-pressure TPAs will windmill due to the flow of propellant going from tank pressure to vacuum. There will be no usable pump output, and the turbine bypass valves will be in the 100% bypass position.

- o Tank Head Start and Idle

The turbopump chilldown is actually completed during the first phase of the tank head start. The start cannot proceed until temperatures are stable at both turbopumps. In the meantime, the low-pressure combustion is heating the thrust chamber and nozzle, and hydrogen and oxygen flowing through their respective regeneratively cooled sections are gaining usable enthalpy. The hydrogen idle valve is modulating to control mixture ratio. Chamber pressure climbs to a few tenths of a psia until it is in equilibrium with the pressure drops from the tanks to the chamber. A stable idle point is reached when the engine operates at pressure and thermal equilibrium.

- o Pumped Idle Operation

The turbine bypass valves are slowly closed as the hydrogen idle valve is closed to divert hydrogen flow through the TPA turbines. Turbopump rotation increases with modulation of the bypass valves to keep mixture ratio within limits. Pumped idle is defined as a stable operating point where pump output exceeds tank pressure and the engine is able to bootstrap into the normal throttle range. The transition from tank head idle to pumped idle is a critical operation, as is the transition beyond pumped idle to the normal throttle range. That range is defined as a chamber pressure of 200 to 2000 psia for 10:1 throttling. The pumps must bootstrap from tank head idle to any point in this range. The bootstrap capability is given by the turbine bypass valve, putting more high energy flow through the TPA turbines.

- o Main Stage - Normal Throttle Range

The turbine bypass valves are designed so that they can rapidly move to a predicted state point with only minimal modulation once that point is reached. Both valves move in unison to a new thrust value, but the hydrogen valve would modulate about the setting to adjust the propellant mixture ratio. This is computed from flowmeter data with a backup check of propellant pressures entering the manifolds of the injector. Valve set points are adjusted after the predicted and actual values are compared.

At low throttle settings, TPA speeds are used to compute flow rate until flowmeter accuracy improves. The regenerator and heat exchanger bypass valves modulate to control propellant temperatures during operation. At all times, the HEX bypass valve limits hot hydrogen flow through the heat exchanger to hold a maximum of 400 F for oxygen entering the turbine. The hydrogen regen bypass valve will increase the bypass any time the hydrogen exiting the baffles is at 900 F or higher. The hydrogen proportioner valve will modulate to optimize the hot-gas side wall temperatures in each circuit.

o Main Stage - Over Thrust (Emergency Power Level)

At maximum over thrust condition, the hydrogen or oxygen turbine bypass valve is saturated (fully closed). The remaining bypass valve is modulated to control mixture ratio. The selection of the saturated bypass valve is dependent on mixture ratio selection. Only coarse thrust control is possible.

o Main Stage - High Mixture Ratio

In order to support missions using lunar oxygen-based propellants, it may be desirable to run the OTV engine in a high mixture ratio (10 to 12:1) condition. This condition requires modifications to the control logic and special coatings for some engine components. The oxygen pump would be run at maximum rated flow rate with thrust modulated by the hydrogen turbine bypass valve.

o Engine Shutdown

Shutdown is somewhat lengthy due to the large residual propellant volume below the main shutoff valves. The propellant residual volumes for the system determine a valve lead or lag time to give the smoothest shutdown transient. To initiate shutdown, the turbine, regenerator, and heat exchanger bypass valves are all commanded to 100% bypass. Then, as the pump pressures are reduced to a safe level, the propellant main shutoff valves are closed and the residual propellants are exhausted from the system. To avoid popping and uneven combustion during the shutdown, the igniter circuit is activated and the igniter valves opened. A shutdown transient is expected to be in the two- to three-second range, depending on throttle position when the shutdown command is given. Residual propellants vaporize and disperse in space as all flow passages in the engine below the shutoff valves remain open to the thrust chamber.

2.3 ENGINE SYSTEM MONITORING

Engine system monitoring includes all functions used to analyze the engine operation, its performance, and ability to perform the required mission. These functions include:

- o Safety Monitoring
- o Diagnostic Monitoring
- o Condition Monitoring
- o Postflight Safing and Condition Assessment

The ICHM operates throughout all engine operational phases. For the purposes of this report, the engine system monitoring functions will be defined as follows:

- o Safety Monitoring

Safety monitoring functions assure safe engine operation. Their objective is to detect any operating condition that endangers the engine or vehicle. These are generally conditions beyond the normal (design) operating envelope of the engine that have not responded to corrective action by the control system. The primary safety monitoring function is to shut down the engine in a safe and expeditious manner. By its nature, safety monitoring is an on-board, real-time function.

- o Diagnostic Monitoring

The diagnostic monitoring function objective is to maintain engine operation as required to complete a given mission. This is accomplished by real-time assessment of engine performance to detect anomalies or off-nominal performance and to provide on-line system adjustments. Engine parameter measurements are used in conjunction with the engine mathematical model to assess engine performance and to detect faulty measurements and sensor failure. Redundant measurements or values derived from analysis are substituted for faulty measurements. Abnormal component performance, including component failures, are corrected by modification of the engine operating set point (when possible).

- Condition Monitoring

Condition monitoring is the function of acquiring the necessary data to assess the overall condition of the engine and its components. This includes parameter measurement, signal conditioning, distributed data processing, data compression and storage, and data transmission. These measurements are used to estimate the useful life of the engine and its components, and its ability to perform future missions. Measurements include those used for control and performance monitoring, along with additional measurements to provide the required data for analysis.

- Postflight Safing and Condition Assessment

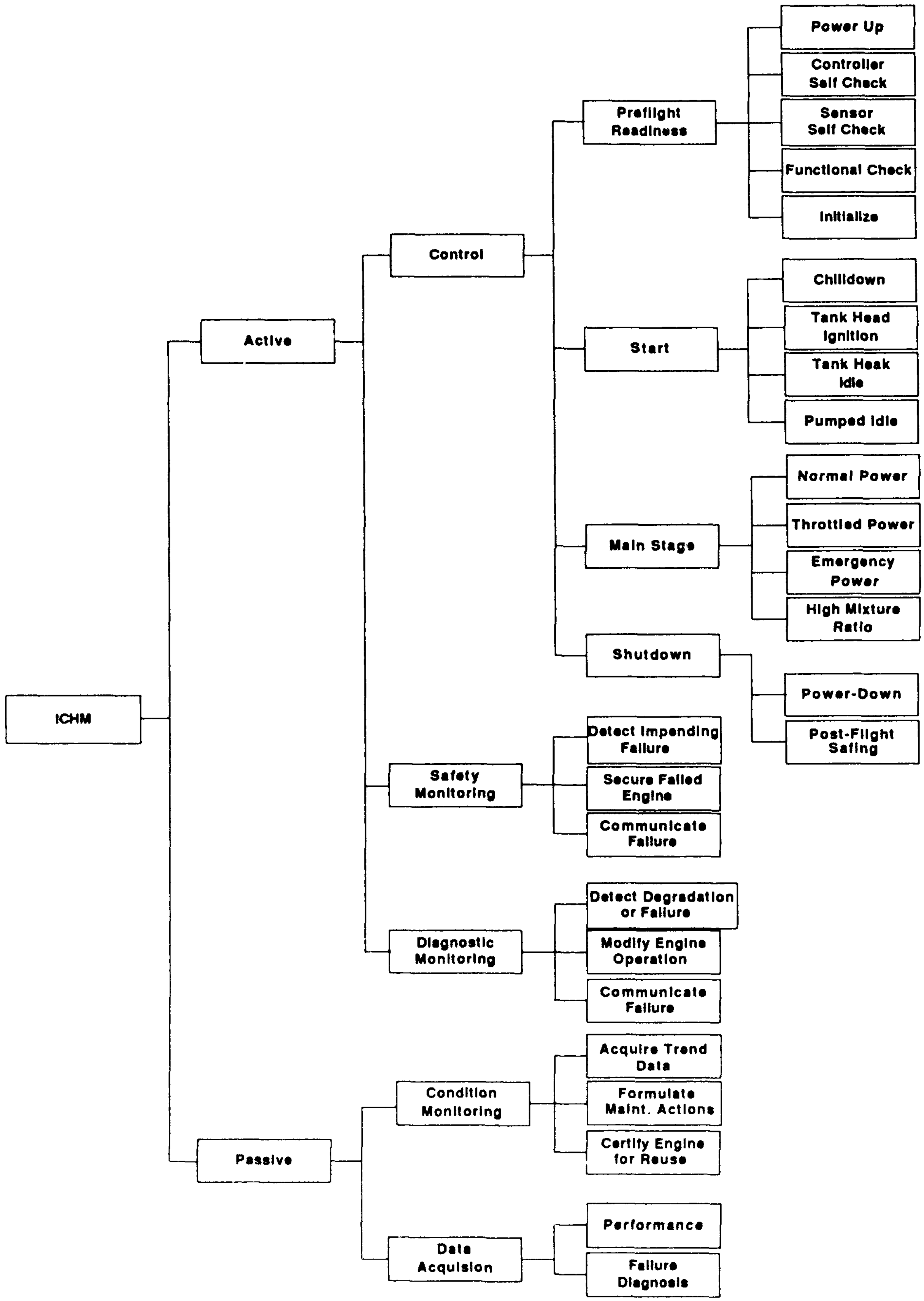
Postflight safing are the functions performed after engine shutdown that are required to safely store it for the next operation. Functional checks are made on the controller, sensors, and control effectors to verify readiness for the next operation. Data from the last flight and previous flights are analyzed to identify failed or degraded components and to determine readiness for the next mission. The remaining service life is estimated by analysis of current data, along with historical patterns.

3.0 MINIMUM OTV ENGINE ICHM FUNCTIONS

Based on the OTV engine preliminary design, the minimally required functions that the ICHM system must perform to operate the engine in space were specified. Control, monitoring, and interface requirements were addressed in detail. The required functions were defined for each major phase and operation of the engine operational cycle, Figure 6.

Figure 6

OTV ICHM Functions



The engine operational cycle was defined in terms of the following phases and operations.

- o Preflight Readiness Assessment
- o Engine Start-Up and Tank Head Idle Control
- o Pumped Idle Control
- o Main Stage and Engine Throttling Control
- o Engine Shutdown Control
- o Safety Monitoring
- o Diagnostic Monitoring
- o Condition Monitoring
- o Post Flight Safing and Condition Assessment
- o Vehicle Interfacing
- o Engine Storage/Removal/Replacement

These phases and operations were decomposed into specific functional requirements. The results of the analyses are presented in Table IV. Included with the definition of each health monitoring and control function are the sub-functions such as measurements or processes which are required for implementation.

Each health monitoring and control measurement was assigned a unique three character symbol. The first character of the symbol indicates the type of measurement, as follows:

L	-	Position Limit
Z	-	Position
I	-	Current
T	-	Temperature
P	-	Pressure
S	-	Speed
F	-	Flowrate
HM	-	Health Monitor Subsystem

The selection of a minimum set of engine control and health monitoring functions is largely dependent on the mission requirements, the acceptable mission risk, and the reusability requirements imposed on the vehicle and engine systems. Many of these parameters remain to be quantified; however, the following assumptions apply to the minimum functions selected in this study.

TABLE IV.A

MINIMUM PREFLIGHT READINESS ASSESSMENT FUNCTIONS

	Function	Symbol
A.1.	Verify Engine Operational Status	
	a. Power Up Controller and Monitoring Systems	---
	b. Controller BIT Sequence	BIT
	c. Sensor BIT Sequence and Calibration	BIT
	d. Initialize Main Propellant Valve Position	
	1. Main H2 Valve (HMSV) Closed	Z28
	2. Main O2 Valve (OMSV) Closed	Z29
	e. Check Functional Controls	
	1. H2 Turbine Bypass Valve (HTBV)	Z21
	2. O2 Turbine Bypass Valve (OTBV)	Z22
	3. HEX Bypass Valve (HEBV)	Z23
	4. H2 Idle Valve (HIV)	Z24
	5. H2 Regen Bypass Valve (HRBV)	Z25
	6. Igniter H2 Valve (HICV)	L01,L02
	7. Igniter O2 Valve (OICV)	L03,L04
	8. H2 Proportioner Valve (HPV)	Z31
	f. Initialize Control Valve Position	
	1. Close H2 Turbine Bypass Valve (HTBV)	Z21
	2. Close O2 Turbine Bypass Valve (OTBV)	Z22
	3. Open HEX Bypass Valve (HEBV)	Z23
	4. Open H2 Idle Valve (HIV)	Z24
	5. Open H2 Regen Bypass Valve (HRBV)	Z25
	6. Close Igniter H2 Valve (HICV)	L01,L02
	7. Close Igniter O2 Valve (OICV)	L03,L04
	8. Neutral H2 Proportioner Valve (HPV)	Z31
A.2.	Verify Engine Position Status	
	a. Extend Nozzle and Verify Status	
	1. Nozzle Position Limit Switches	L09-L14
	2. Nozzle Latch Position	L15-L17
	3. Actuator Motor Current Draw	I01-I03
	b. Gimbal Actuator Position/Self Test	
	1. Actuator Positions and Limits	Z27,Z30
	2. Actuator Slew Rate	Software
	3. Actuator Motor Current Draw	I04,I05
A.3.	Determine Engine Inlet Conditions	
	a. H2 Inlet Pressure	Vehicle
	b. H2 Inlet Temperature	Vehicle
	c. O2 Inlet Pressure	Vehicle
	d. O2 Inlet Temperature	Vehicle

TABLE IV.B

MINIMUM ENGINE START-UP AND TANK HEAD IDLE CONTROL FUNCTIONS

	Function	Symbol
B.1.	Chilldown O2 TPA	
	a. Open Main O2 Valve (OMSV)	Z29
	b. Open Igniter O2 Valve (OICV)	L03,L04
	c. Monitor O2 Pump Outlet Temperature	T08
	d. Close Main O2 Valve (OMSV)	Z29
	e. Close Igniter O2 Valve (OICV)	L03,L04
B.2.	Chilldown H2 TPA	
	a. Open Main H2 Valve (HMSV)	Z28
	b. Open Igniter H2 Valve (HICV)	L01,L02
	c. Monitor H2 Pump Outlet Temperature	T01
B.3.	Lightoff - Tank Head Start	
	a. Energize Igniter	I06
	b. Open Main O2 Valve (OMSV)	Z29
	c. Open Igniter O2 Valve (OICV)	L03,L04
	d. Confirm Ignition/Monitor Chamber Pressure	P12
B.4.	Tank Head Idle Control	
	a. Control Idle Mixture Ratio	
	1. Modulate H2 Idle Valve (HIV)	Z24
	2. Monitor H2 Flowrate	F01,P01,T01
	3. Monitor O2 Flowrate	F04,P08,T08
	b. Modulate HEX Bypass Valve (HEBV)	Z23
	1. Monitor O2 Turbine Inlet Temperature	T09
	c. Modulate H2 Regen Bypass Valve (FRBP)	Z25
	1. Measure H2 Turbine Inlet Temperature	T04
	d. Confirm Stable Ignition	
	1. Monitor Chamber Pressure	P12
	e. Deactivate Igniter	
	1. Close Igniter O2 Valve (OICV)	L03,L04
	2. Close Igniter H2 Valve (HICV)	L01,L02
	3. De-energize Igniter	I06

TABLE IV.C

MINIMUM PUMPED IDLE CONTROL FUNCTIONS

	Function	Symbol
C.1.	Control Mixture Ratio	
	a. Close H2 Idle Valve (HIV)	Z24
	b. Modulate H2 Turbine Bypass Valve	
	1. Monitor H2 Turbine Bypass Valve (HTBV)	Z21
	2. Monitor H2 Flowrate	F01,P01,T01
	c. Modulate O2 Turbine Bypass Valve	
	1. Monitor O2 Turbine Bypass Valve (OTBV)	Z22
	2. Monitor O2 Flowrate	F04,P08,T08
C.2.	Control Turbine Inlet Temperatures	
	a. Modulate H2 Regen Bypass Valve	
	1. Monitor H2 Regen Bypass Valve (HRBV)	Z25
	2. Measure H2 Turbine Inlet Temperature	T04
	b. Modulate HEX Bypass Valve	
	1. Monitor HEX Bypass Valve (HEBV)	Z23
	2. Measure O2 Turbine Inlet Temperature	T09
C.3.	Control Engine Thrust	
	a. Monitor Chamber Pressure	P12
	b. Adjust H2 Turbine Bypass Valve	
	1. Monitor H2 Turbine Bypass Valve (HTBV)	Z21
	c. Adjust O2 Turbine Bypass Valve	
	1. Monitor O2 Turbine Bypass Valve (OTBV)	Z22
C.4.	Control Autogenous Tank Feedline Pressure	
	a. Cycle O2 Tank Pressurization Valve (OTPV)	L05,L06
	1. Monitor O2 Inlet Pressure	P11
	2. Monitor O2 Tank Pressure	Vehicle
	b. Cycle H2 Tank Pressurization Valve (FTPV)	L07,L08
	1. Monitor H2 Inlet Pressure	P07
	2. Monitor H2 Tank Pressure	Vehicle

TABLE IV.D

MINIMUM MAIN STAGE AND THROTTLING CONTROL FUNCTIONS

	Function	Symbol
D.1.	Control Mixture Ratio	
	a. Modulate H2 Turbine Bypass Valve	
	1. Monitor H2 Turbine Bypass Valve (HTBV)	Z21
	2. Monitor H2 Flowrate	F01,P01,T01
	b. Modulate O2 Turbine Bypass Valve	
	1. Monitor O2 Turbine Bypass Valve (OTBV)	Z22
	2. Monitor O2 Flowrate	F04,P08,T08
D.2.	Control Turbine Inlet Temperatures	
	a. Modulate H2 Regen Bypass Valve	
	1. Monitor H2 Regen Bypass Valve (HRBV)	Z25
	2. Measure H2 Turbine Inlet Temperature	T04
	b. Modulate HEX Bypass Valve	
	1. Monitor HEX Bypass Valve (HEBV)	Z23
	2. Measure O2 Turbine Inlet Temperature	T09
D.3.	Control Engine Thrust	
	a. Monitor Chamber Pressure	P12
	b. Adjust H2 Turbine Bypass Valve	
	1. Monitor H2 Turbine Bypass Valve (HTBV)	Z21
	c. Adjust O2 Turbine Bypass Valve	
	1. Monitor O2 Turbine Bypass Valve (OTBV)	Z22
D.4.	Control Combustion Device Temperature	
	a. Modulate H2 Proportioner Valve	
	1. Monitor H2 Proportioner Valve (HPV)	Z31
	2. Measure Chamber H2 Outlet Temperature	T15
	3. Measure Baffle H2 Outlet Temperature	T23
D.5.	Control Autogenous Tank Feedline Pressure	
	a. Cycle O2 Tank Pressurization Valve (OTPV)	L05,L06
	1. Monitor O2 Inlet Pressure	P11
	2. Monitor O2 Tank Pressure	Vehicle
	b. Cycle H2 Tank Pressurization Valve (FTPV)	L07,L08
	1. Monitor H2 Inlet Pressure	P07
	2. Monitor H2 Tank Pressure	Vehicle

TABLE IV.E

MINIMUM ENGINE SHUTDOWN CONTROL FUNCTIONS

	Function	Symbol
E.1.	Activate Igniter	
	a. Open Igniter H2 Valve (HICV)	L01,L02
	b. Open Igniter O2 Valve (OICV)	L03,L04
	c. Energize Igniter	I06
E.2.	Shutdown Autogenous Tank Feedline Pressurization	
	a. Close O2 Tank Pressurization Valve (OTPV)	L05,L06
	b. Close H2 Tank Pressurization Valve (FTPV)	L07,L08
E.3.	Shutdown O2 TPA	
	a. Open O2 Turbine Bypass Valve	
	1. Monitor O2 Turbine Bypass Valve (OTBV)	Z22
	b. Open HEX Bypass Valve	
	1. Monitor HEX Bypass Valve (HEBV)	Z23
	2. Measure O2 Turbine Inlet Temperature	T09
	c. Monitor O2 Pump Outlet Pressure	P08
	d. Close Main O2 Valve (OMSV)	Z29
E.4.	Shutdown H2 TPA	
	a. Open H2 Turbine Bypass Valve	
	1. Monitor H2 Turbine Bypass Valve (HTBV)	Z21
	b. Open H2 Regen Bypass Valve	
	1. Monitor H2 Regen Bypass Valve (HRBV)	Z25
	2. Measure H2 Turbine Inlet Temperature	T04
	c. Open H2 Idle Valve (HIV)	Z24
	d. Monitor H2 Pump Outlet Pressure	P01
	e. Close Main H2 Valve (HMSV)	Z28
E.5.	Verify Shutdown	
	a. Monitor Chamber Pressure	P12
	b. Close Igniter H2 Valve (HICV)	L01,L02
	c. Close Igniter O2 Valve (OICV)	L03,L04
	d. De-energize Igniters	I06

TABLE IV.F

MINIMUM SAFETY MONITORING FUNCTIONS

	Function	Symbol
F.1.	High, Uncontrollable Turbine Inlet Temperature	
	a. Measure H2 Turbine Inlet Temperature	T04
	b. Measure O2 Turbine Inlet Temperature	T09
F.2.	Uncontrollable Mixture Ratio	
	a. Monitor H2 Flowrate	F01,P01,T01
	b. Monitor O2 Flowrate	F04,P08,T08
F.3.	Uncontrollable Chamber Pressure	
	a. Monitor Chamber Pressure	P12
F.5.	Turbopump Overspeed	
	a. Monitor H2 Pump Speed	S01,S03
	b. Monitor O2 Pump Speed	S05
F.6.	Turbopump Bearing Failure	
	a. Monitor H2 TPA Bearing Condition	
	1. Monitor H2 Bearing/Shaft Displ.	Z01,Z02,Z04 Z06,Z07,Z09
	2. Monitor H2 TPA Vibration	Z05
	3. Monitor H2 TPA Speed	S01,S03
	b. Monitor O2 TPA Bearing Condition	
	1. Monitor O2 Bearing/Shaft Displ.	Z13,Z14,Z16
	2. Monitor O2 TPA Vibration	Z17
	3. Monitor O2 TPA Speed	S05
F.7.	O2 Turbopump Fire	
	a. Monitor O2 Pump Outlet Temperature	T08
	b. Monitor O2 Turbine Outlet Temperature	T10
F.8.	Plume Anomaly Exceeds Thresholds	
	a. Monitor Plume Spectral Emissions	HM1
F.9.	Propellant Leak Magnitude Exceeds Threshold	
	a. Monitor H2 Propellant Leaks	HM2
	b. Monitor O2 Propellant Leaks	HM3
F.9.	Engine Compartment Fire/Explosion	
	a. Monitor Engine Compartment Temperatures	T24-T27

Table IV.F (cont.)

Function	Symbol
F.10. Excessive Nozzle Hot Gas Leak	
a. Monitor Extendible/Retractable Nozzle Status	
1. Nozzle Position Limit Switches	L09-L14
2. Nozzle Latch Position	L15-L17
3. Hot Gas Seal Leak	T28-T30
F.11. Uncontrollable Thrust Vector	
a. Monitor Gimbal Actuator Status	
1. Actuator Positions	Z27,Z30
2. Actuator Slew Rate	Software
3. Actuator Motor Current Draw	I04,I05

TABLE IV.G

MINIMUM DIAGNOSTIC MONITORING FUNCTIONS

	Function	Symbol
G.1.	Controller Self Test	BIT
G.2.	Sensor Fault Detection and Accommodation	
	a. Test Anomalous Sensor Data	Software, BIT
	b. Compare Parameters to Math Model	Software
	c. Isolate Faulty Parameters	Software
	d. Compute Replacement Parameters	Software
G.3.	Component Failure Detection and Accommodation	
	a. Test Anomalous Sensor Data	Software, BIT
	b. Compare Parameters to Math Model	Software
	c. Define Component Failure Mode	Software
	d. Compute Mission Risk	Software
	d. Compute Reconfiguration Parameters	Software
G.4.	Performance Failure Detection and Accommodation	
	a. Test Anomalous Sensor Data	Software, BIT
	b. Compare Parameters to Math Model	Software
	c. Calculate H2 Pump Efficiencies	Software
	d. Calculate O2 Pump Efficiencies	Software
	e. Calculate HEX Efficiencies	Software
	f. Calculate TCA Thermal Efficiencies	Software
	g. Define Performance Failure Mode	Software
	h. Compute Mission Risk	Software
	i. Compute Reconfiguration Parameters	Software

TABLE IV.H

MINIMUM CONDITION MONITORING FUNCTIONS

	Function	Symbol
H.1.	Data Acquisition and Signal Processing	
	a. H2 Turbopump Axial Shaft Displacement	Z01,Z06
	b. H2 Turbopump Radial Shaft Displ.	Z02,Z04,Z07,Z09
	c. H2 Turbopump Vibration	Z05
	d. H2 Turbopump Speed	S01,S03
	e. H2 Pump Discharge Pressure	P01
	f. H2 Pump Discharge Temperature	T01
	g. H2 Pump Flow	F01
	h. H2 Turbine Inlet Pressure	P05
	i. H2 Turbine Inlet Temperature	T04
	j. H2 Boost Pump Inlet Pressure	P07
	k. H2 Boost Pump Inlet Temperature	T07
	l. H2 Boost Pump Bearing Deflection	Z10,Z11
	m. H2 Boost Pump Speed	S06
	n. O2 Turbopump Axial Shaft Displacement	Z13
	o. O2 Turbopump Radial Shaft Displ.	Z14,Z16
	p. O2 Turbopump Vibration	Z17
	q. O2 Turbopump Speed	S05
	r. O2 Pump Discharge Pressure	P08
	s. O2 Pump Discharge Temperature	T08
	t. O2 Pump Flow	F04
	u. O2 Turbine Inlet Pressure	P10
	v. O2 Turbine Inlet Temperature	T09
	w. O2 Boost Pump Inlet Pressure	P11
	x. O2 Boost Pump Inlet Temperature	T11
	y. O2 Boost Pump Bearing Deflection	Z18,Z19
	z. O2 Boost Pump Speed	S07
	aa. Combustion Chamber Pressure	P12
	ab. Injector H2 Inlet Pressure	P13
	ac. Injector H2 Inlet Temperature	T13
	ad. Injector O2 Inlet Pressure	P14
	ae. Injector O2 Inlet Temperature	T14
	af. Chamber H2 Coolant Outlet Temperature	T15
	ag. Nozzle H2 Coolant Inlet Pressure	P17
	ah. Nozzle O2 Coolant Inlet Pressure	P18
	ai. Nozzle O2 Coolant Inlet Temperature	T19
	aj. H2 Regenerator Inlet Pressure	P02
	ak. H2 Regenerator Outlet Temperature	T21
	al. H2 Baffle Coolant Inlet Pressure	P15
	am. H2 Baffle Coolant Outlet Temperature	T23

Table IV.H (cont.)

Function	Symbol
an. MCC Throat Temperature	T17
ao. H2 Turbine Bypass Valve Position	Z21
ap. O2 Turbine Bypass Valve Position	Z22
aq. HEX Bypass Valve Position	Z23
ar. H2 Idle Valve Position	Z24
as. H2 Regen Bypass Valve Position	Z25
at. H2 Main Valve Position	Z28
au. O2 Main Valve Position	Z29
av. Nozzle Position and Status	
1. Nozzle Position Limit Switches	L09-L14
2. Nozzle Latch Position	L15-L17
3. Actuator Motor Current Draw	I01-I03
4. Hot Gas Seal Leak	T28-T30
aw. Gimbal Position and Status	
1. Actuator Positions	Z27,Z30
2. Actuator Slew Rate	Software
3. Actuator Motor Current Draw	I04,I05
ax. Engine Compartment Temperatures	T24-T27
ay. Plume Spectral Emission Intensities	HM1
az. H2 Leak Rate and Location	HM2
ba. O2 Leak Rate and Location	HM3
H.2. Data Handling	
a. Data Compression	Software
b. Data Storage	Optical Disk
c. Data Transmission	Telemetry Feed

TABLE IV.I

MINIMUM POST FLIGHT SAFING AND CONDITION ASSESSMENT FUNCTIONS

	Function	Symbol
I.1.	Engine Position Settings	
	a. Retract/Lock-up Nozzle	
	1. Nozzle Position Limit Switches	L09-L14
	2. Nozzle Latch Position	L15-L17
	3. Actuator Motor Current Draw	I01-I03
	4. Hot Gas Seal Leak	T28-T30
	b. Center/Lock-up Gimbal Actuators	
	1. Actuator Positions	Z27,Z30
	2. Actuator Slew Rate	Software
	3. Actuator Motor Current Draw	I04,I05
I.2.	Engine Status Check	
	a. Controller BIT Sequence	BIT
	b. Sensor BIT Sequence	BIT
	c. Main Propellant Valve Position	
	1. Main H2 Valve (HMSV) Closed	Z28
	2. Main O2 Valve (OMSV) Closed	Z29
	d. Functional Controls Check	
	1. H2 Turbine Bypass Valve (HTBV)	Z21
	2. O2 Turbine Bypass Valve (OTBV)	Z22
	3. HEX Bypass Valve (HEBV)	Z23
	4. H2 Idle Valve (HIV)	Z24
	5. H2 Regen Bypass Valve (HRBV)	Z25
	6. Igniter H2 Valve (HICV)	L01,L02
	7. Igniter O2 Valve (OICV)	L03,L04
	8. H2 Proportioner Valve (HPV)	Z31
I.3.	Identify Failed or Degraded Components	
	a. Upload Data Storage to Vehicle	Optical Disk
	b. Data Analysis	Ground Ops.
	c. Maintenance Requirements Identified	Ground Ops.
	d. Life Prediction/Certification	Ground Ops.
I.4.	Power Down Controller and Diagnostic Systems	---

TABLE IV.J

MINIMUM VEHICLE INTERFACE FUNCTIONS

	Function	Symbol
J.1.	Command and Control	
	a. Receive Vehicle Control Commands	---
	b. Verify Control Response	---
	c. Verify Engine Performance	---
	d. Identify Safety Anomalies/Request Shutdown	---
J.2.	Data Control	
	a. Receive Vehicle Data Requests	---
	b. Return Vehicle Data Requests	---
	c. Send Telemetry Data	---
J.3.	Power	
	a. Receive Vehicle Power	---
	b. Backup Power Switching	---

TABLE IV.K

MINIMUM ENGINE STORAGE/REMOVAL/REPLACEMENT FUNCTIONS

	Function	Symbol
K.1.	Power and Thermal Conditioning	
	a. Receive Vehicle Power	---
	b. Backup Power Switching	---
	c. Thermal Conditioning	---
K.2.	Environment Monitoring	
	a. Monitor Controller Temperature	T31
	b. Monitor Instrument System Temperatures	T32-T34
	c. Monitor Valve and Actuator Temperatures	T35-T46
	d. Monitor Radiation and Hazards	TBD

- **Mission Requirements**

The ICHM system must be flexible and robust to accommodate multiple mission profiles, including orbit transfer, lunar transfer, and lunar lander missions. This flexibility will require advanced control and monitoring capabilities to track deep throttling and high mixture ratio operating conditions using a single ICHM configuration.[1, 2]

The engine will be space based, resulting in requirements for long-duration space exposure, zero gravity engine start and restart, automated preflight readiness assessment, and limited automated diagnostics. Automated diagnostics are considered a "gray area" for a minimum ICHM system, but would certainly be incorporated in an advanced system. The acceptable level of mission risk is a primary factor governing the use of automated diagnostics in the minimum ICHM system. Mission risk is reduced by the application of automated diagnostics for the purposes of adaptive or contemplative control in the event of component degradation or failure. In addition, growth potential is enhanced by incorporating limited automated diagnostics into the first-generation (or minimum) ICHM system.

NASA's constraints on this study dictated the engine will not be inspected or maintained in space. Each engine will be treated as an orbital replacable unit (ORU). This results in a requirement that the engine be certified for reuse based solely on engine operating data and history. This, in turn, leads to a requirement for advanced ground based diagnostics and component life prediction capability.

- **Mission Risk**

The engine and vehicle will be man-rated and reusable. The vehicle must be fail operational. Fail operational requirements will be met through engine out capability. No advanced adaptive control strategies for management of engine failure, such as reduced power level operation, were detailed by this study. However, the development of these adaptive control algorithms was recognized and can be accommodated in this ICHM system through the insertion of appropriate control and diagnostic software. The combined engine and ICHM system must be fail-safe. The ICHM system requirement was assumed to be fail operational for a single ICHM failure and fail-safe for a second failure. This means the ICHM system must be capable of safely shutting down (or locking up) an engine following a second ICHM system failure. All critical ICHM systems will be redundant.

The level of acceptable mission risk for the OTV vehicle system requires further definition. In all probability, very low mission risk will be mandated due to the high value of the man-rated vehicle and payload. Mission risk will be reduced through fail operational, fail-safe design, redundancy, and the incorporation of advanced control and monitoring features.

Redundancy requirements were assessed in Subtask II of this study and are discussed in Section 4.0. Redundancy by means of inter-engine data comparison was considered as an advanced function and was not addressed.

- **Reusability**

The engine must be fully reusable, without ground maintenance, for 20 complete missions consisting of 100 engine starts and 4 hours of firing duration. The engine operational life must be 100 complete missions consisting of 500 engine starts and 20 hours of firing duration. The 4-hour/20-mission service-free life places heavy demands on the capabilities of the on-board monitoring systems to ensure mission safety, reduce mission risk, and provide adequate data for ground based diagnostics and component life prediction (for engine certification between missions).

4.0 MINIMUM OTV ENGINE ICHM ELEMENTS

A comprehensive list of the elements comprising the minimum ICHM system was prepared. The list was based on the 7500-lbF OTV engine design and the results of Subtask I, which specified the minimally required ICHM functions. All elements of the ICHM system were addressed to approximately equal levels of detail, including (1) sensors, (2) signal processors, (3) harnesses, (4) engine controller, (5) control effectors, (6) engine control algorithms, (7) health assessment algorithms, and (8) vehicle interfaces.

The minimum OTV engine control model requirements were defined in terms of the engine control diagram presented in Figure 7. Each box in Figure 7 defines a single control model element. Control valve locations and key condition monitoring sensors are shown on the simplified engine schematic presented in Figure 8.

Control gains and schedule definitions require a detailed simulation capability for the engine and control systems. These simulations must be capable of accurately modeling the transient and steady-state operating characteristics of the engine and control systems.

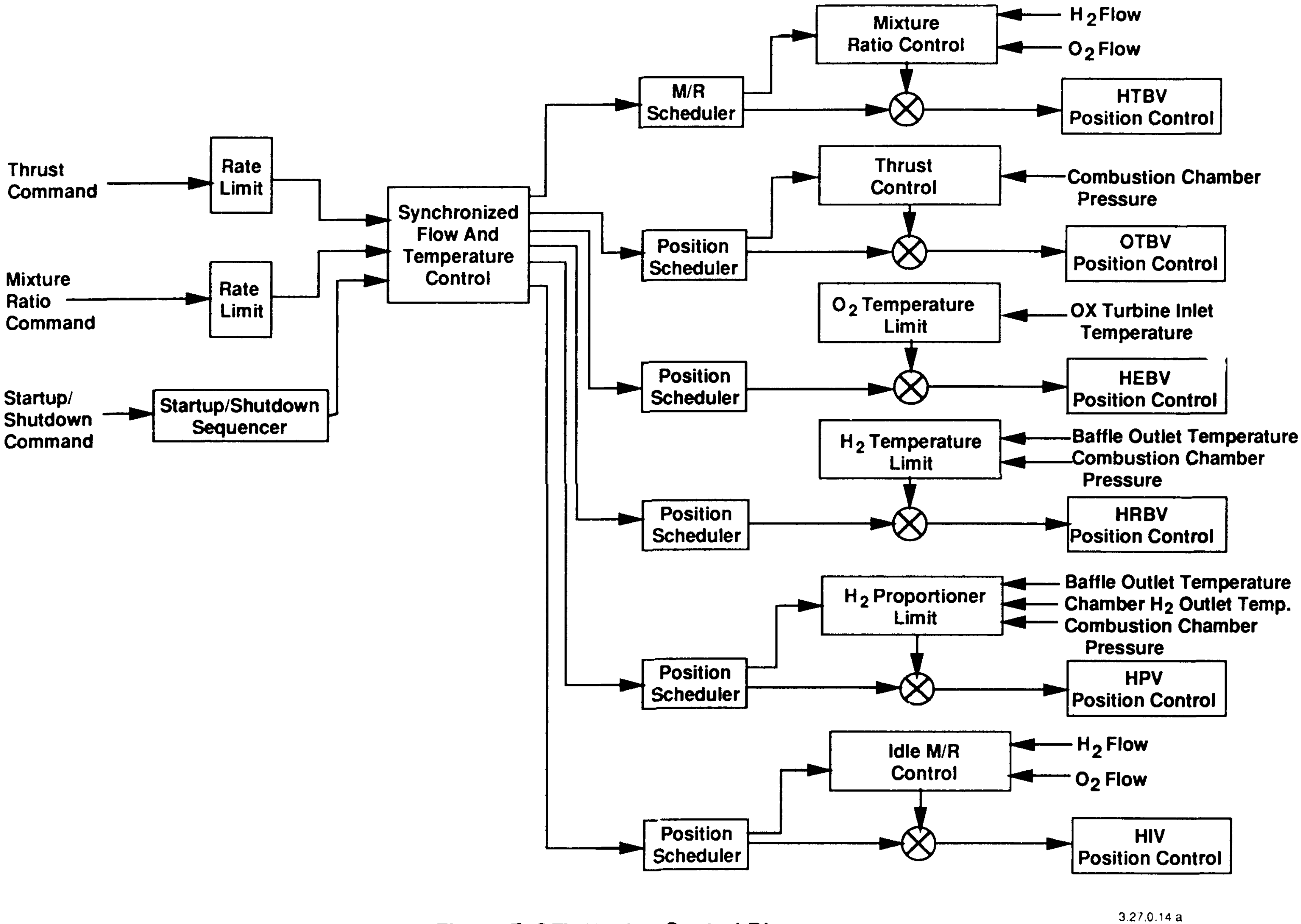


Figure 7. OTV Engine Control Diagram

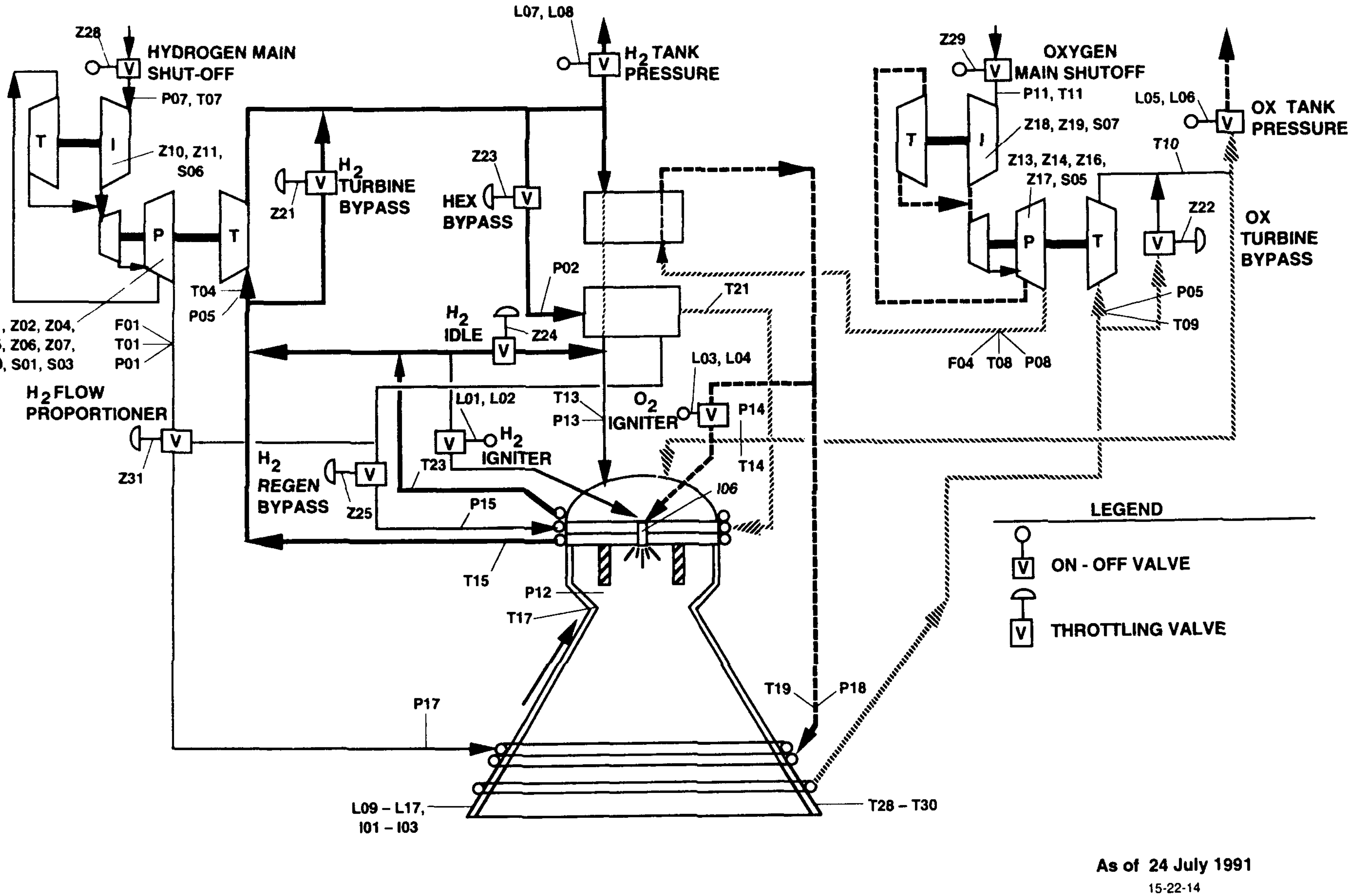


Figure 8. OTV Engine Dual Expander Cycle Control Valve Schematic

Advanced simulation capability is a necessary precursor to design and development of an OTV ICHM system. Advanced simulation capabilities for cryogenic rocket engine systems are available at Aerojet based on application of the CRETS (Cryogenic Rocket Engine Transient Simulation) and M-LETS (Modified Liquid Engine Transient Simulation) codes using the AD-100 analog/digital hybrid computer.[3]

The minimum OTV engine ICHM system elements were defined based on the ICHM system architecture presented in Figure 9. The Engine Control Unit architecture was further defined based on Aerojet's AREC II (Advanced Rocket Engine Controller) as presented in Figures 10 and 11. Key features of the AREC II architecture include the following.

1) Modular elements are built on a standard backplane bus providing flexibility to accommodate growth and multiple mission applications, e.g., orbit transfer, lunar transfer, lunar lander.

2) The backplane bus provides the capability for multiple parallel processors, e.g., parallel control and monitoring computer units.

3) The modular architecture accommodates rapid hardware and software prototyping as well as variable redundancy at minimum cost.

4) AREC II is based on state-of-the-art hardware and software including VLSI/Hybrid CMOS technologies.

5) AREC II incorporates advanced fault tolerance and reliability enhancement techniques.

The list defining the minimum ICHM system elements for the 7,500-lbF OTV engine is presented in Table V. The list is organized based on the following fifteen categories: A) Control Computer Unit; B) Monitoring Computer Unit; C) Triple Channel 1553B Module; D) General Output Electronics; E) Low Speed Input Electronics; F) High Speed Input Electronics; G) Interchannel Communications; H) Control Software; I) Monitoring Software; J) Power Supply Electronics; K) Mass Data Storage; L) Harnesses; M) Distributed Signal Conditioners; N) Control Effectors; and O) Sensors.

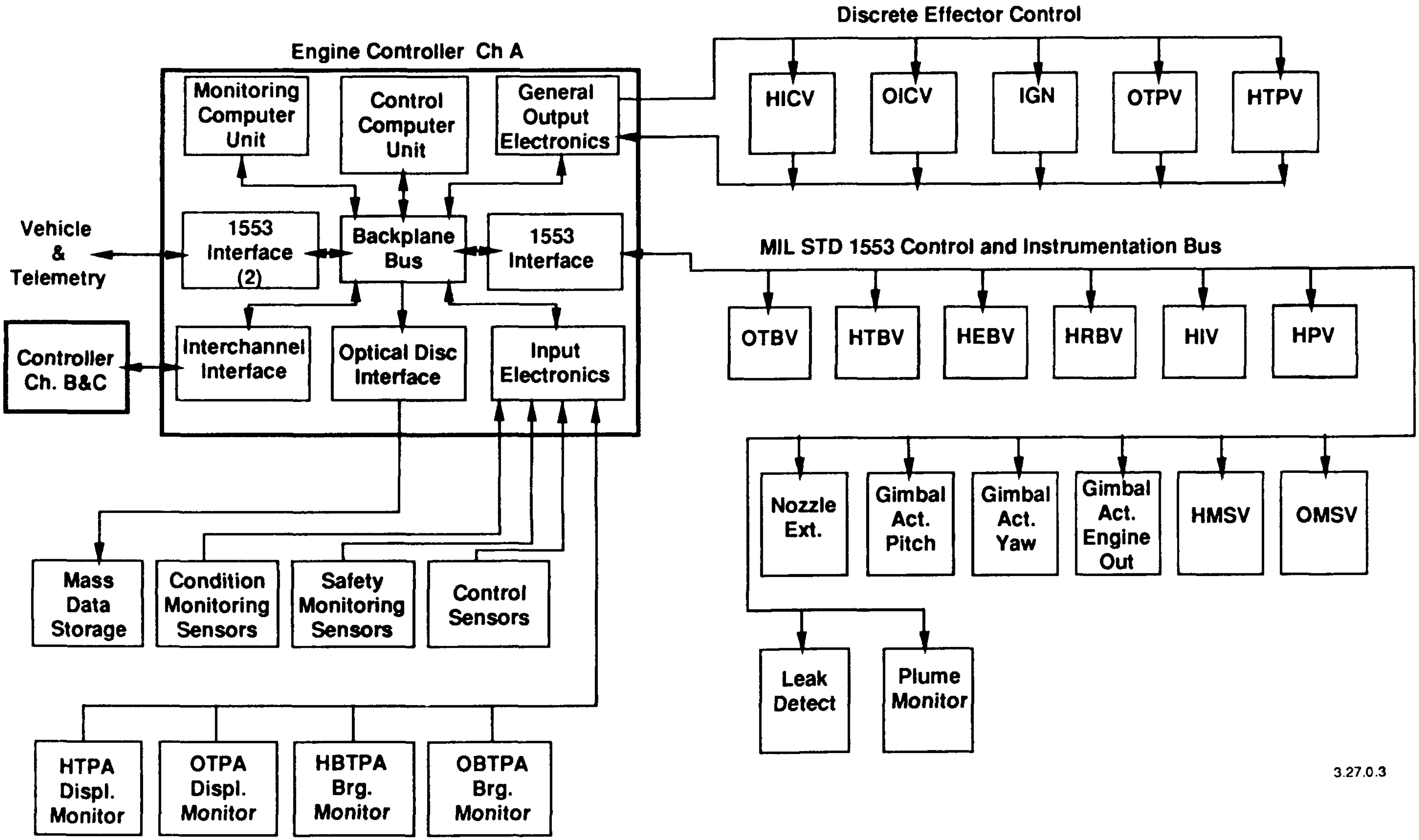


Figure 9. OTV Engine Minimum Integrated Control and Health Monitoring System Element Diagram

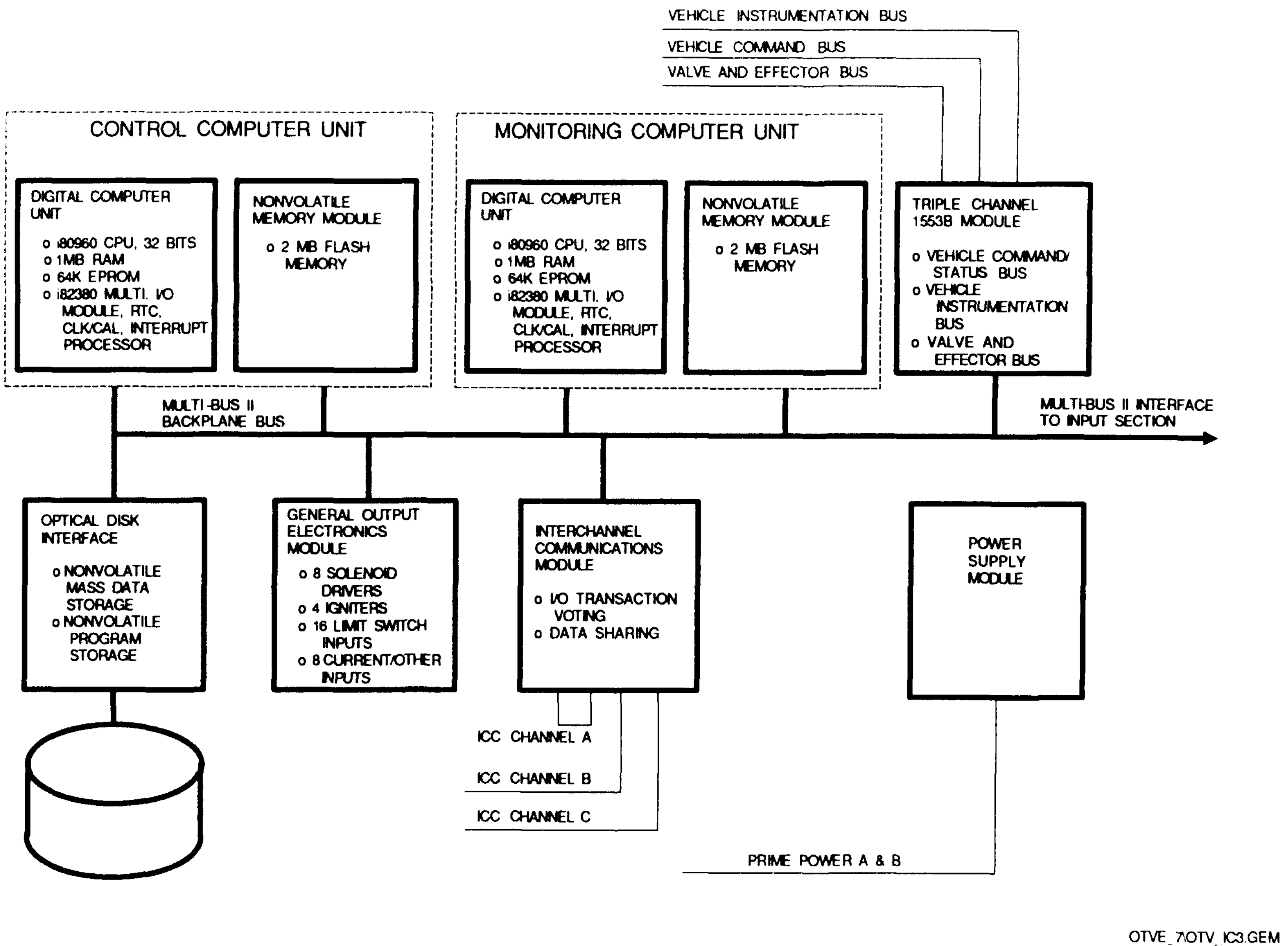


Figure 10a. Modular OTV ICHM Engine Controller Architecture Processor and Output Section, Channel A

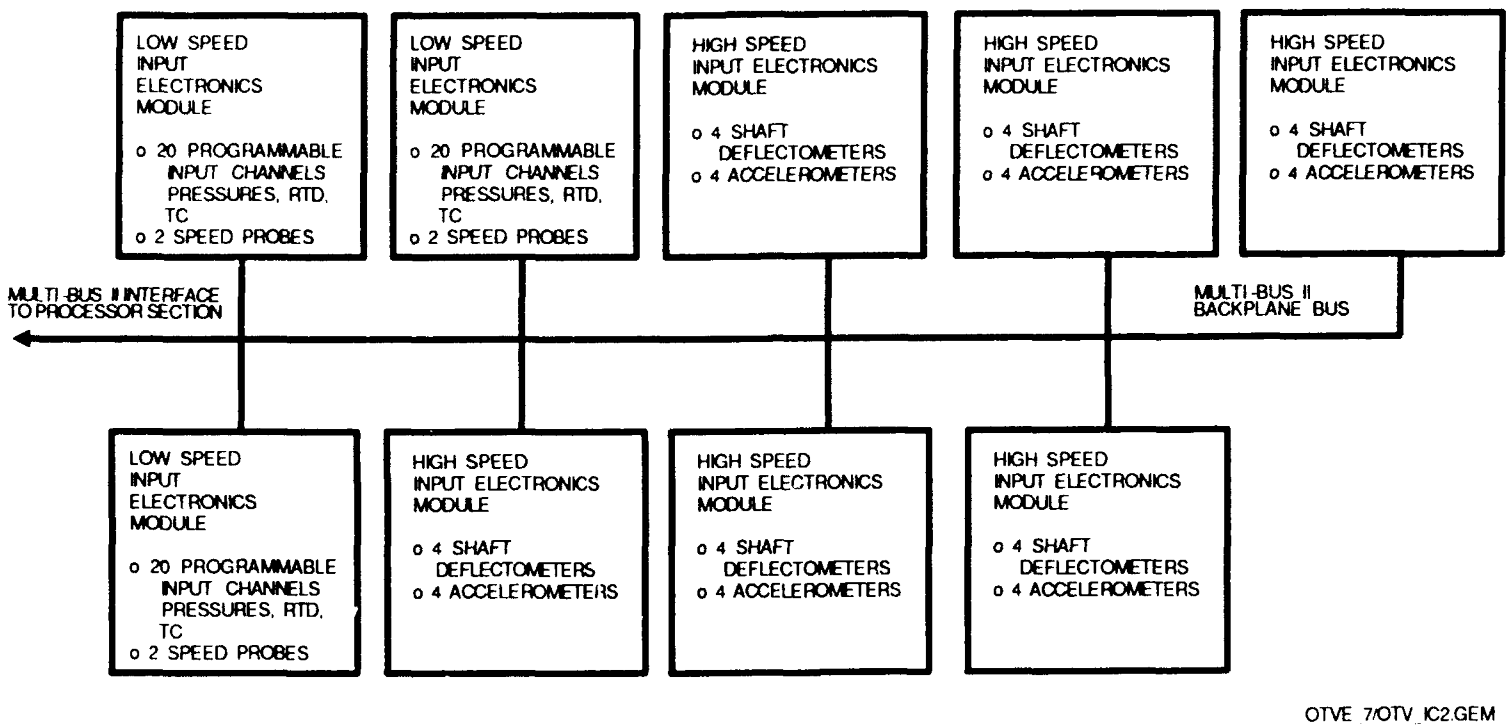
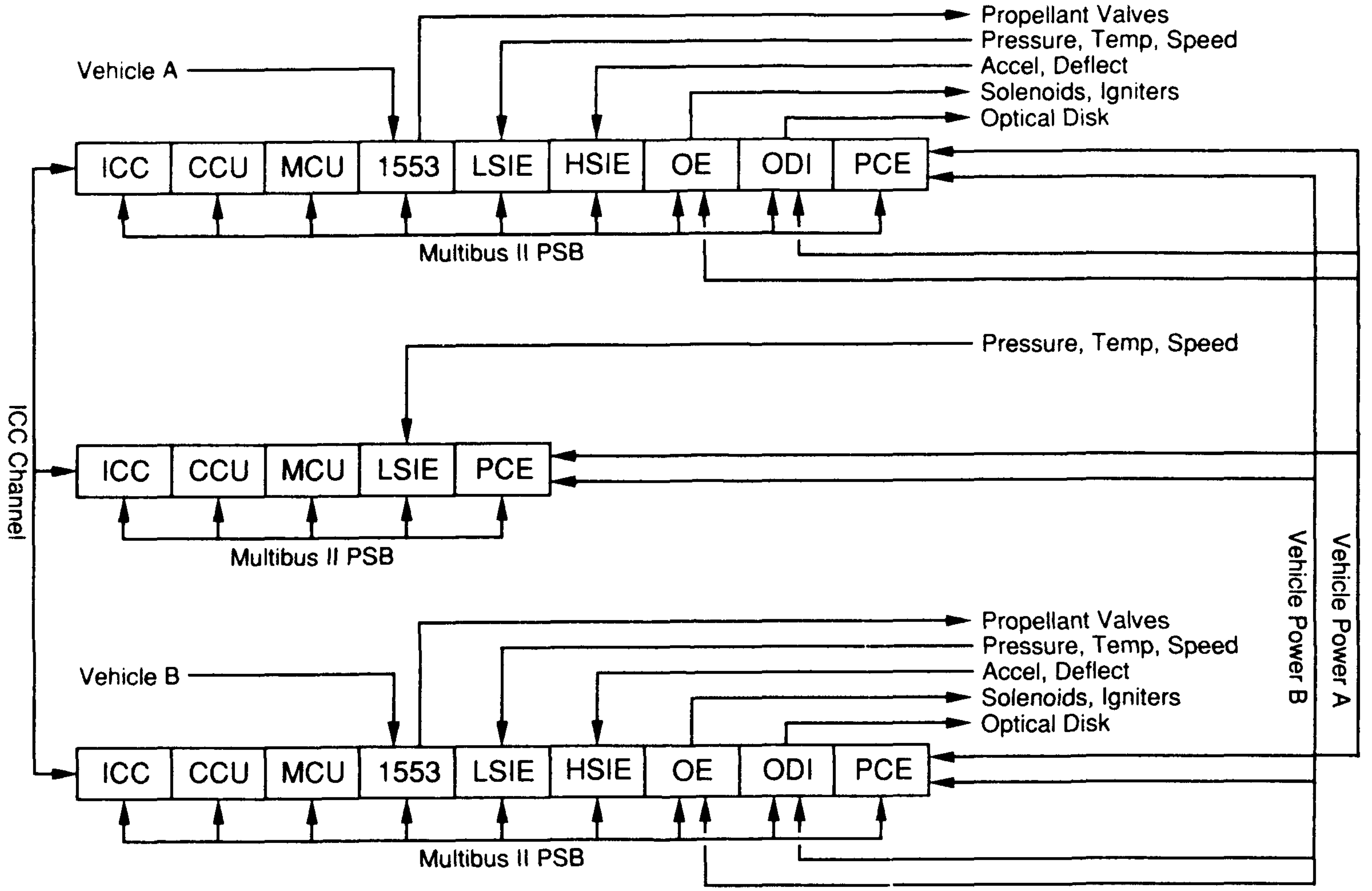


Figure 10b. Modular OTV ICHM Engine Controller Architecture Input Section, Channel A



ICC	Inter-Channel Communications
CCU	Control Computer Unit
MCU	Monitoring Computer Unit
LSIE	Low Speed Input Electronics
HSIE	High Speed Input Electronics
OE	Output Electronics
ODI	Optical Disk Interface
PCE	Power Control Electronics

1.11.7.06

Figure 11. OTV ICHM Engine Controller Top Level System Interconnection

Tables V.A though V.O describe the Engine Controller elements. Each of these elements are resident within the controller housing. The Control Computer Unit, Table V.A, is responsible for control data processing including MIL-STD 1553 interface management (three dual channels), backplane bus management, engine effector control, red-line monitoring, and vehicle interface functions.

SSME experience has shown that ample memory and throughput are important factors in the life cycle cost and versatility of a reusable rocket engine controller. The elements selected for the minimum OTV ICHM system combine 64-kB EPROM, 1-MB Static RAM, and 2-MB flash memory with 20-MIPS maximum throughput to meet all anticipated computational requirements. More importantly, the modular architecture selected is adaptable and provides significant growth capability through module upgrade and/or additions.

The engine monitoring system operates in parallel with the engine controller to verify sensor data and to monitor the condition of the engine and its components. The Monitoring Computer Unit DCU and memory modules, Table V.B, are interchangeable with those used for engine control. This feature enhances reliability and versatility while reducing cost.[4]

The minimum OTV ICHM system monitoring computer performs limited contemplative functions including sensor failure detection and parameter estimation, performance monitoring and diagnostic monitoring. Failures identified by the monitoring system generate an interrupt and a failure ID code which are reported to the control computer via the backplane bus. In an advanced version of the OTV ICHM system, the monitoring computer may advise the control computer of probable risks, adaptive control strategies and red-line values, and gain schedules. Incorporating the monitoring computer system in the minimum OTV ICHM system provides the growth option for these advanced capabilities. Additional system growth may be provided through the distributed processing of "smart" sensor packages which evaluate as well as measure engine parameters.

The vehicle interfaces with the engine controller through a MIL-STD-1553 bidirectional digital interface, Table V.C. A second MIL-STD-1553 interface is used for telemetry and a third to communicate with the engine control effectors and the distributed signal conditioners. The MIL-STD 1773 fiber optic digital interface is a growth option and is considered an advanced capability within the framework of this study.

TABLE V

OTV ENGINE MINIMUM ICHM SYSTEM ELEMENTS

A.	**CONTROL COMPUTER UNIT:**		**TYPE:**
	1.	Digital Computer Unit (DCU)	Channels A, B, C
		a. Central Processor Unit (CPU)	Intel i80960 based 32 bit RISC processor 32-bit bus width 20 MIPs throughput max 4GB potential address space HCMOS VLSI and ASIC technologies
		b. Bootstrap Memory	64KB EPROM
		c. Program Execution Memory	1MB Static RAM
		d. Interrupt Controller	i82380
		e. Four Counter Timers	i82380
		f. DMA Controller	i82380
		g. Serial/GSE Interface	8 bit serial interface 82510 UART 1488 transmitter 1489 receiver 26LS31 transmitter 26LS32 receiver
		h. MultiBus II Interface	82389 MPC
	2.	Nonvolatile Memory Unit (NMU)	Channels A, B, C
		a. Nonvolatile Program Memory	2MB flash memory
		b. MultiBus II Interface	
B.	**MONITORING COMPUTER UNIT:**		**TYPE:**
	1.	Digital Computer Unit (DCU)	Channels A, B, C
		a. Central Processor Unit (CPU)	Intel i80960 based 32 bit RISC processor 32-bit bus width 20 MIPs throughput max 4GB potential address space HCMOS VLSI and ASIC technologies
		b. Bootstrap Memory	64KB EPROM
		c. Program Execution Memory	1MB Static RAM
		d. Interrupt Controller	i82380

Table V (Cont.)

	e.	Four Counter Timers	i82380
	f.	DMA Controller	i82380
	g.	Serial/GSE Interface	8 bit serial interface 82510 UART 1488 transmitter 1489 receiver 26LS31 transmitter 26LS32 receiver
	h.	MultiBus II Interface	82389 MPC
2.		Nonvolatile Memory Unit (NMU)	Channels A, B, C
	a.	Nonvolatile Program Memory	2MB flash memory
	b.	MultiBus II Interface	

C. <u>TRIPLE CHANNEL 1553B MODULE:</u> <u>TYPE:</u>

1.		Vehicle Interface	Channels A and B Dual (Redundant) Channel MIL-STD 1553B
2.		Vehicle Telemetry Interface	Channels A and B Dual (Redundant) channel MIL-STD 1553B
3.		Valve and Effector Interface	Channels A and B Dual (Redundant) channel MIL-STD 1553B
	a.	Servo Valve Functions	HTBV control/monitoring OTBV control/monitoring HEBV control/monitoring HRBV control/monitoring HIV control/monitoring HPV control/monitoring HMSV control/monitoring OMSV control/monitoring
	b.	Extendible Nozzle Functions	Extension/retraction Position monitoring
	c.	Gimbal Actuators	Pitch act./mon., Ch. A Pitch act./mon., Ch. B Yaw act./mon., Ch. A Yaw act./mon., Ch. B Engine out pitch act.
	d.	Distributed Monitoring	Hydrogen leak detection Oxygen leak detection Plume spectrometer

Table V (Cont.)

4.	MultiBus II Interface	Channels A and B
D.	**GENERAL OUTPUT ELECTRONICS:**	**TYPE:**
1.	Output Switch	Channels A and B ASIC based WDT control input 32-bit storage register
2.	Command Decoder	Channels A and B Selects device chip Software driven
3.	Solenoid Valve Drivers	Channels A and B < 1 msec switch time HICV driver OICV driver OTPV driver HTPV driver
4.	Igniter Drivers	Channels A and B Igniter A driver Igniter B driver
5.	MultiBus II Interface	Channels A and B
6.	Flow Sensor Inputs	
	a. Solenoid Valve Position	Open/closed
	b. Igniter Monitor	Igniter A on/off Igniter B on/off
E.	**LOW SPEED INPUT ELECTRONICS (LSIE):**	**TYPE:**
1.	General Signal Cond. & Selection	Channels A, B, C ASIC based
	a. Input Select Control	Selects chip Software driven
	b. Input Data Register (IDR)	FIFO data buffer
	c. A/D Converters	+/-5 Vdc input 12-bit word output 10 microsec max. conv.
	d. Temperature Sensor Inputs	Filter Calibration input signal

Table V (Cont.)

	e.	Pressure Sensor Inputs	Filter Calibration input signal
	f.	Flow Sensor Inputs	Pulse to digital conv. Clock for V to f conv.
	g.	Power Supply BIT Inputs	TBD
2.	MultiBus II Interface		Channels A, B, C

F. <u>HIGH SPEED INPUT ELECTRONICS (HSIE):</u> <u>TYPE:</u>

1.	A/D Converters		Channels A and B ASIC based 8-bit word output 5 microsec max conv
2.	Capacitive Displacement Sensor Inputs		Channels A and B
	a.	Hydrogen TPA monitor	Summing amplifier Linearizer
	b.	Oxygen TPA monitor	Summing amplifier Linearizer
	c.	Hydrogen boost pump mon.	Summing amplifier Linearizer
	d.	Oxygen boost pump monitor	Summing amplifier Linearizer
3.	Accelerometer Inputs		Channels A and B
	a.	Signal Processing	FFT
4.	MultiBus II Interface		Channels A and B

G. <u>INTERCHANNEL COMMUNICATIONS (ICC):</u> <u>TYPE:</u>

1.	Input Select Control	Channels A, B, C Selects chip Software driven
2.	Data Registers	Channels A, B, C Data buffers and registers
3.	Voting Circuit/Software	Channels A, B, C Bit by bit Fault tolerant clock
4.	MultiBus II Interface	Channels A, B, C

Table V (Cont.)

H.	CONTROL SOFTWARE:	TYPE:
1.	Operating System	UNIX based derivative
2.	Executive Program	Ada
3.	Vehicle I/F	Ada
4.	Monitoring System I/F	Ada
5.	Interchannel Communication	Ada
6.	Power Up/Preflight Sequencer	Ada
7.	Engine Start/Tank Head Idle	Ada
8.	Pumped Idle	Ada
9.	Main Stage/Throttling Thrust	Ada
10.	Main Stage/Throttling MR	Ada
11.	Shutdown/Post Flight Safing	Ada
12.	Red-line Assessment/Emergency Shutdown	Ada
13.	Fault Response Control (Library)	Ada
14.	Built-In Test	Ada

I.	DIAGNOSTIC MONITORING SOFTWARE:	TYPE:
1.	Operating System	TBD
2.	Executive Program	Expert system
3.	Controller I/F	Ada
4.	Interchannel Communication	Ada
5.	Preflight Readiness Assessment	Expert system/Ada
6.	Set Red-Line Values	Ada
7.	Real Time Model	Ada
8.	Sensor Data Validation	Ada
9.	Sensor Failure ID	Expert System/Ada
10.	Parameter Est./Update IDR	Ada
11.	Performance Validation	Ada
12.	Performance Failure ID	Expert system/Ada
13.	Performance Fault Control Seq. ID	Ada
14.	Component Health Validation	Ada
15.	Component Failure ID	Expert system/Ada
16.	Component Fault Control Seq. ID	Ada
17.	Post Flight Condition Assessment	Ada
18.	ICHM Environment Monitoring	Ada
19.	Built-In Test	Ada

J.	POWER SUPPLY ELECTRONICS:	TYPE:
1.	Input Conditioning	Channel A, B, C EMI filtered Power failure sensing

Table V (Cont.)

	2.	Controller/Monitor Power Supply	Channel A, B, C MIL-STD 1539 compatible Regulated 28-Vdc Voltage monitor Power failure sensing Power failure interrupt I/O & I/F supply
	3.	ICHM Heater Power Supply	Channel A only Unregulated 28-Vdc Power-up only
K.	**MASS DATA STORAGE:**		**TYPE:**
	1.	Data Archive	Optical disk drive
	2.	MultiBus II Interface	Channels A and B
L.	**HARNESSES:**		**TYPE:**
	1.	Monitoring Sensor Harness (Control, Safety, and Condition)	Analog Electric Signal and Power
	2.	Solenoid Control Valve Power Harness	28 VDC Electric Power
	3.	Triple Channel 1553 Command and Data Bus	Vehicle Command Bus Vehicle Inst./Telemetry Bus Valve and Effector Bus
M.	**DISTRIBUTED SIGNAL CONDITIONERS:**		**TYPE:**
	1.	O_2 Leak Sensor	Sensor Element, Digital Data Processing MIL-STD 1553 Interface
	2.	H_2 Leak Sensor	Sensor Element, Digital Data Processing MIL-STD 1553 Interface
	3.	Plume Anomaly Sensors	Spectral Analyzer, Data Processing MIL-STD 1553 Interface
	4.	H_2 TPA Displacement and Speed	Capacitive Sensor, Signal Conditioner, Analog Data Transmission
	5.	O_2 TPA Displacement and Speed	Capacitive Sensor, Signal Conditioner, Analog Data Transmission
	6.	H_2 Boost Pump Displacement and Speed	Capacitive Sensor, Signal Conditioner, Analog Data Transmission

Table V (Cont.)

7.	O_2 Boost Pump Displacement and Speed	Capacitive Sensor, Signal Conditioner, Analog Data Transmission

N. CONTROL EFFECTORS: TYPE:

1.	HMSV H_2 Main Shutoff Valve	EM Actuator Driven Ball MIL-STD 1553 Interface
2.	OMSV O_2 Main Shutoff Valve	EM Actuator Driven Ball MIL-STD 1553 Interface
3.	HTBV H_2 Turbine Bypass Valve	EM Actuator Driven Pintle MIL-STD 1553 Interface
4.	OTBV O_2 Turbine Bypass Valve	EM Actuator Driven Pintle MIL-STD 1553 Interface
5.	HRBV H_2 Regenerator Bypass Valve	EM Actuator Driven Pintle MIL-STD 1553 Interface
6.	HEBV HEX Bypass Valve	EM Actuator Driven Pintle MIL-STD 1553 Interface
7.	HIV H_2 Idle Valve	EM Actuator Driven Pintle MIL-STD 1553 Interface
8.	HPV H_2 Flow Proportioner Valve	EM Actuator Driven Pintle MIL-STD 1553 Interface
9.	OTPV Ox Tank Pressurization Valve	Solenoid Operated Poppet
10.	HTBV Fuel Tank Pressurization Valve	Solenoid Operated Poppet
11.	HICV Igniter H_2 Control Valve	Solenoid Operated Poppet
12.	OICV Igniter O_2 Control Valve	Solenoid Operated Poppet
13.	IGN Igniter	Direct Electrical Powered
14.	EN Extendable Nozzle	EM Act. Driven Ball Screw MIL-STD 1553 Interface
15.	GAP1 Gimbal Actuator, Pitch #1	EM Linear Actuator MIL-STD 1553 Interface
16.	GAP2 Gimbal Actuator, Pitch #2	EM Linear Actuator MIL-STD 1553 Interface
17.	GAY1 Gimbal Actuator, Yaw #1	EM Linear Actuator MIL-STD 1553 Interface
18.	GAY2 Gimbal Actuator, Yaw #2	EM Linear Actuator MIL-STD 1553 Interface
19.	GAEO Gimbal Actuator, Engine Out	EM Linear Actuator MIL-STD 1553 Interface

O. SENSORS: TYPE:

1. O2 TPA

a.	T08a Pump Discharge Temperature	Pt RTD

Table V (Cont.)

b.	T08b	Pump Discharge Temperature	Pt RTD
c.	T09a	Turbine Inlet Temperature	Type K T/C
d.	T09b	Turbine Inlet Temperature	Type K T/C
e.	T10a	Turbine Discharge Temperature	Type K T/C
f.	T10b	Turbine Discharge Temperature	Type K T/C
g.	P08a	Pump Discharge Pressure	Strain Gage
h.	P08b	Pump Discharge Pressure	Strain Gage
i.	P10	Turbine Inlet Pressure	Strain Gage
j.	F04a	Pump Flowrate	Vortex Shedding Flowmeter
k.	F04b	Pump Flowrate	Vortex Shedding Flowmeter
l.	S05a	Pump Speed, 0	Capacitive Displ. Sensor
m.	S05b	Pump Speed, 90	Capacitive Displ. Sensor
n.	Z13a	Shaft Axial Displacement, 0	Capacitive Displ. Sensor
o.	Z13b	Shaft Axial Displacement, 90	Capacitive Displ. Sensor
p.	Z14	Shaft Radial Displacement, 0	Capacitive Displ. Sensor
q.	Z16	Shaft Radial Displacement, 90	Capacitive Displ. Sensor
r.	Z17a	TPA Vibration #1	Piezoelectric Accelerometer
s.	Z17b	TPA Vibration #1	Piezoelectric Accelerometer
t.	Z22a	O_2 Turbine Bypass Valve Position	LVDT
u.	Z22b	O_2 Turbine Bypass Valve Position	LVDT

2. O_2 Boost Pump

a.	T11	Inlet Temperature	Pt RTD
b.	P11	Inlet Pressure	Strain Gage
c.	S07	Speed	Capacitive Displ. Sensor
d.	Z18	Bearing Outer Race Deflectometer	Capacitive Displ. Sensor
e.	Z19	Bearing Outer Race Deflectometer	Capacitive Displ. Sensor

3. H_2 TPA

a.	T01a	Pump Discharge Temperature	Pt RTD
b.	T01b	Pump Discharge Temperature	Pt RTD
c.	T04a	Turbine Inlet Temperature	Type K T/C
d.	T04b	Turbine Inlet Temperature	Type K T/C
e.	P01a	Pump Discharge Pressure	Strain Gage
f.	P01b	Pump Discharge Pressure	Strain Gage
g.	P05	Turbine Inlet Pressure	Strain Gage
h.	F01a	Flowrate #1	Vortex Shedding Flowmeter
i.	F01b	Flowrate #2	Vortex Shedding Flowmeter
j.	S01a	Pump Speed-1st Stage, 0	Capacitive Displ. Sensor
k.	S01b	Pump Speed-1st Stage, 90	Capacitive Displ. Sensor
l.	S03a	Pump Speed-2nd Stage, 0	Capacitive Displ. Sensor
m.	S03b	Pump Speed-2nd Stage, 90	Capacitive Displ. Sensor
n.	Z01a	Shaft Axial Displ.-1st Stage, 0	Capacitive Displ. Sensor
o.	Z01b	Shaft Axial Displ.-1st Stage, 90	Capacitive Displ. Sensor
p.	Z02	Shaft Radial Displ.-1st Stage, 0	Capacitive Displ. Sensor

Table V (Cont.)

q.	Z04	Shaft Radial Displ.-1st Stage, 90	Capacitive Displ. Sensor
r.	Z06a	Shaft Axial Displ.-2nd Stage, 0	Capacitive Displ. Sensor
s.	Z06b	Shaft Axial Displ.-2nd Stage, 90	Capacitive Displ. Sensor
t.	Z07	Shaft Radial Displ.-2nd Stage, 0	Capacitive Displ. Sensor
u.	Z09	Shaft Radial Displ.-2nd Stage, 90	Capacitive Displ. Sensor
v.	Z05a	TPA Vibration #1	Piezoelectric Accelerometer
w.	Z05b	TPA Vibration #1	Piezoelectric Accelerometer
x.	Z21a	Turbine Bypass Valve	LVDT
y.	Z21b	Turbine Bypass Valve	LVDT
4.	**H_2 Boost Pump**		
a.	T07	Boost Pump Inlet Temperature	Pt RTD
b.	P07	Boost Pump Inlet Pressure	Strain Gage
c.	S06	Boost Pump Speed	Capacitive Displ. Sensor
d.	Z10	Bearing Outer Race Deflect.	Capacitive Displ. Sensor
e.	Z11	Bearing Outer Race Deflect.	Capacitive Displ. Sensor
5.	**TCA**		
a.	T13	Injector H_2 Inlet Temperature	Type K T/C
b.	T14	Injector O_2 Inlet Temperature	Type K T/C
c.	T15	Chamber H_2 Coolant Outlet Temp.	Type K T/C
d.	T17	MCC Throat Temperature	Type K T/C
e.	T19	Nozzle O_2 Coolant Inlet Temp.	Type K T/C
f.	T23	Baffle H_2 Outlet Temperature	Type K T/C
g.	P12a	Chamber Pressure	Strain Gage
h.	P12b	Chamber Pressure	Strain Gage
i.	P13	Injector H_2 Inlet Pressure	Strain Gage
j.	P14	Injector O_2 Inlet Pressure	Strain Gage
k.	P15	Baffle H_2 Coolant Inlet Pressure	Strain Gage
l.	P17	Chamber H_2 Coolant Inlet Pressure	Strain Gage
m.	P18	Nozzle O_2 Coolant Inlet Pressure	Strain Gage
n.	HM1	Plume Spectral Emission Analyzer	Fabry-Perot Interferometric Spectrometer
6.	**HEX**		
a.	Z23a	HEX Bypass Valve Position	LVDT
b.	Z23b	HEX Bypass Valve Position	LVDT
7.	**H2 Regenerator**		
a.	T21	Regen. H_2 Outlet Temperature	Type K T/C
b.	P02	Regen. H_2 Inlet Pressure	Strain Gage
c.	Z25a	Regen. Bypass Valve Position #1	LVDT
d.	Z25b	Regen. Bypass Valve Position #2	LVDT

Table V (Cont.)

8. Nozzle Extension

a.	L09	Nozzle Position	Limit Switch
b.	L10	Nozzle Position	Limit Switch
c.	L11	Nozzle Position	Limit Switch
d.	L12	Nozzle Position	Limit Switch
e.	L13	Nozzle Position	Limit Switch
f.	L14	Nozzle Position	Limit Switch
g.	L15	Nozzle Latch Position	Limit Switch
h.	L16	Nozzle Latch Position	Limit Switch
i.	I01	Actuator Motor Current Draw	Current Sensor
j.	I02	Actuator Motor Current Draw	Current Sensor
k.	T28	Ball Screw Bearing #1 Temp.	Type K T/C
l.	T29	Ball Screw Bearing #2 Temp.	Type K T/C
m.	T30	Ball Screw Bearing #3 Temp.	Type K T/C

9. Gimbal Actuator

a.	Z27a	Pitch #1 Actuator Position	LVDT
b.	Z27b	Pitch #2 Actuator Position	LVDT
c.	Z30a	Yaw #1 Actuator Position	LVDT
d.	Z30b	Yaw #2 Actuator Position	LVDT
e.	I04	Actuator Motor Current Draw	Current Sensor
f.	I05	Actuator Motor Current Draw	Current Sensor

10. O_2 Feed/Tank

a.	P11	O_2 Tank Inlet Pressure	Strain Gage
b.	Z29	Main O_2 Valve Position	RVDT
c.	L05	O_2 Tank Press. Valve Position	Limit Switch
d.	L06	O_2 Tank Press. Valve Position	Limit Switch

11. H_2 Feed/Tank

a.	P07	H_2 Tank Inlet Pressure	Strain Gage
b.	Z28	Main H_2 Valve Position	LVDT
c.	L07	H_2 Tank Press. Valve Position	Limit Switch
d.	L08	H_2 Tank Press. Valve Position	Limit Switch

12. Igniter

a.	L01	Igniter H_2 Valve Position	Limit Switch
b.	L02	Igniter H_2 Valve Position	Limit Switch
c.	L03	Igniter O_2 Valve Position	Limit Switch
d.	L04	Igniter O_2 Valve Position	Limit Switch
e.	I06	Igniter Spark Current	Current Sensor

Table V (Cont.)

13. Engine Compartment

a.	T24	Engine Compartment Temperature	Type K T/C
b.	T25	Engine Compartment Temperature	Type K T/C
c.	T26	Engine Compartment Temperature	Type K T/C
d.	T27	Engine Compartment Temperature	Type K T/C
e.	HM2	H_2 Propellant Leak Sensor	Sensor Net
f.	HM3	O_2 Propellant Leak Sensor	Sensor Net

14. Idle Valve

a.	Z24a	H_2 Idle Valve Position	LVDT
b.	Z24b	H_2 Idle Valve Position	LVDT

15. Proportioner Valve

a.	Z31a	H_2 Proportioner Valve Position	LVDT
b.	Z31b	H_2 Proportioner Valve Position	LVDT

Solenoid valves and the igniter are controlled directly by solenoid drivers within the engine controller general output electronics, Table V.D. Each General Output Electronics module provides for control of up to eight solenoid valves, two igniters, plus two spares. Valve position and igniter current sensor feedback are incorporated in the General Output Electronics module using bilevel data inputs for 16 limit switches, two current monitors, plus six spares. Other discrete sensor outputs are routed to the control unit input electronics.

The engine controller input electronics include the Low Speed Input Electronics (LSIE) and High Speed Input Electronics (HSIE) modules, Tables V.E and V.F. Precision voltage references and built-in-test are provided by each LSIE for up to 20 software programmable instrumentation channels (pressure, temperature, position) plus two speed or flowrate (pulse) channels. Each HSIE module provides digital signal processing for up to four shaft deflectometers plus four accelerometers, including hardware fast fourier transform (FFT) algorithm capability.

The Interchannel Communications (ICC) module, Table V.G, provides for data exchange and bit-by-bit I/O transaction voting between the three redundant controller channel input and output parameters. The ICC module is central to the fail operational, fail safe requirement assumed for the minimum OTV ICHM system.

The engine control and monitoring software elements, Tables V.H and V.I respectively, incorporate portable Ada procedural code for all control functions plus expert system capability for diagnostic functions. The complex control and monitoring requirements for the OTV engine, including the necessary mission flexibility, will require an appreciable software library resident within the control and monitoring computer units. A limited library of failure response control strategies is included as an element of the minimum OTV ICHM system software to accommodate 1996 state-of-the-art rocket engine diagnostic and adaptive control algorithms.

The power supply control electronics (PCE), Table V.J, provides filtered and regulated power as required to all ICHM systems. Failure sensing electronics provide a warning interrupt to preserve controller memory state in the event of input power failure. Preserving memory state will enable reliable control system restart and recovery from brief input power failures.

Mass data storage is provided by reading and writing to an optical data disk across the backplane bus, Table V.K. Mass data storage is provided for sensor data to allow for post flight diagnostic and condition assessment of the engine systems. Sophisticated post flight analyses, including remaining life prediction, will be required to certify the engine for reuse without return to earth for inspection and maintenance. Nonvolatile storage of control and diagnostic software will also be provided so that these functions may be reloaded if required.

Analog and digital electrical harnesses are identified in Table V.L. The analog power and instrumentation harness bundling was based primarily on sensor function for this study, i.e., individual harness bundles for control sensors, safety monitoring sensors, and diagnostic monitoring sensors. However, in final design, the bundling will be better accommodated based on engine layout and sensor location. The digital MIL-STD-1553 bus provides for exchange of command and instrumentation data and is used as the primary interface to the modulated control effectors. The MIL-STD 1773 fiber optic digital interface is a growth option and is considered an advanced capability within the framework of this study.

A limited number of distributed signal conditioning units were identified as part of the minimum OTV ICHM system, Table V.M. Three of these are self-contained sensor packages which communicate with the control unit via the MIL-STD-1553 bus. They include two "smart" propellant leak detection systems and the plume monitoring spectrometer.[5,6] Additionally, the turbopump's capacitive bearing and displacement monitors require an oscillator and limited signal conditioning in close proximity to the sensors.[7] In the minimum OTV ICHM system the turbopump monitor signals are input to the engine controller via the high speed input electronics. An advanced system would incorporate distributed data processing for the turbopump monitors as well as other "smart" sensor packages.

The control effector list provided in Table V.N includes 19 actuators and control valves. Two types of engine control effectors were considered: (1) direct driven units such as solenoid valves and igniters which are connected to drivers within the engine controller general output electronics; and (2) electromechanical actuator driven devices such as control valves, gimbal actuators and the extendible nozzle actuators which are connected to the MIL-STD 1553 command and data bus. The electromechanical actuator driven devices use brushless D.C. motor drivers with integral driver electronics and internal sensors to measure position, current, and temperature. They are intelligent devices which communicate with the engine controller through the MIL-STD-1553 bus.

The minimum OTV ICHM system sensor list, provided in Table V.O, includes a total of 118 individual and redundant sensors. This list is based on the minimally required ICHM functions defined in Subtask I and is organized according to the component monitored. Included with each sensor identification is a brief description of the sensor type.

All cryogenic fluid temperature measurements are made with immersion-type platinum resistance temperature detectors (Pt RTDs), which have stable and accurate temperature-resistance relationships. Near ambient and high temperature measurements up to 1500 F will be made with standard Type K (chromel-alumel) thermocouples. Immersion T/Cs are used for gas temperature measurements, and surface mounted T/Cs will be used for measuring hardware temperature. Fluid pressure measurements are all made with strain gage transducers. Flowrates are measured with vortex shedding flowmeters.

Turbopump vibration is measured using piezoelectric accelerometers. Pump speed, shaft displacement, and deflection are measured using capacitive displacement sensors.

Valve position is measured using either limit switches for on/off-type valves or LVDTs for monitoring the position of metering valves.

Current draw by the gimbal actuators, nozzle extension, and spark igniters is measured using inductive current sensors. Propellant leak detection is based on a collection of sensors assembled into a sensor net. Plume spectral emissions are analyzed using an interferometric spectrometer.

5.0 TECHNOLOGY READINESS OF MINIMAL ICHM SYSTEM

The current technology readiness of the minimally required control and monitoring features of the OTV ICHM system has been estimated using the rating scale listed below. These levels are standardized by the NASA Office of Exploration for comparing technology options for future mission choices. Included with the descriptions provided by NASA is a brief interpretive description by Aerojet (in parentheses).

Technology Readiness Levels

Level 7	System validation model demonstrated in space. (Final or equivalent system configuration.)
Level 6	System validation model demonstrated in simulated environment. (Final or equivalent system configuration.)
Level 5	Component and/or breadboard demonstrated in relevant environment. (Unit of similar design.)
Level 4	Component and/or breadboard demonstrated in laboratory. (Critical function and/or characteristic demonstrated.)
Level 3	Analytical and experimental critical function and/or characteristic proof-of-concept. (Conceptual design tested analytically or experimentally.)
Level 2	Technology concept/application formulated. (Conceptual design formulated.)
Level 1	Basic principles observed and reported.

It should be noted that Levels 4 and 5 are associated with component development, while Levels 6 and 7 are associated with system model development.

The technology readiness assessments made for each system element are reported in Table VI. The technical readiness level of the individual sensor components was determined as follows: all RTDs, T/Cs, strain gage pressure transducers, piezoelectric accelerometers, LVDTs, RVDTs, and limit switches were determined to be Level 7, since they are routinely used in space engine systems.[8]

The technical readiness level of capacitive displacement sensors, vortex shedding flowmeters, the Fabry-Perot interferometric spectrometer, and current sensors were determined to be Level 4, since they have not yet been demonstrated in space but have been demonstrated in laboratory environments.

The technical readiness level of the O_2 and H_2 propellant leak sensors were determined to be Level 1 and 2+, respectively.

TABLE VI

OTV ENGINE MINIMUM ICHM SYSTEM TECHNOLOGY READINESS ASSESSMENT

A. CONTROL COMPUTER UNIT:	TECH. READINESS LEVEL:
1. Digital Computer Unit (DCU)	4
a. Central Processor Unit (CPU)	
b. Bootstrap Memory	
c. Program Execution Memory	
d. Interrupt Controller	
e. Four Counter Timers	
f. DMA Controller	
g. Serial/GSE Interface	
h. MultiBus II Interface	
2. Nonvolatile Memory Unit (NMU)	4
a. Nonvolatile Program Memory	
b. MultiBus II Interface	

B. MONITORING COMPUTER UNIT:	TECH. READINESS LEVEL:
1. Digital Computer Unit (DCU)	4
a. Central Processor Unit (CPU)	
b. Bootstrap Memory	
c. Program Execution Memory	
d. Interrupt Controller	
e. Four Counter Timers	
f. DMA Controller	
g. Serial/GSE Interface	
h. MultiBus II Interface	
2. Nonvolatile Memory Unit (NMU)	4
a. Nonvolatile Program Memory	
b. MultiBus II Interface	

C. TRIPLE CHANNEL 1553B MODULE:	TECH. READINESS LEVEL:
1. Vehicle Interface	5
2. Vehicle Telemetry Interface	5
3. Valve and Effector Interface	5
a. Servo Valve Functions	
b. Extendible Nozzle Functions	
c. Gimbal Actuators	
d. Distributed Monitoring	
4. MultiBus II Interface	4 or 5

Table VI (Cont.)

		TECH. READINESS LEVEL:
D.	**GENERAL OUTPUT ELECTRONICS:**	**TECH. READINESS LEVEL:**
1.	Output Switch	4
2.	Command Decoder	4
3.	Solenoid Valve Drivers	5
4.	Igniter Drivers	5
5.	MultiBus II Interface	5
6.	Flow Sensor Inputs	5
	a. Solenoid Valve Position	
	b. Igniter Monitor	
E.	**LOW SPEED INPUT ELECTRONICS (LSIE):**	**TECH. READINESS LEVEL:**
1.	General Signal Cond. & Selection	5
	a. Input Select Control	
	b. Input Data Register (IDR)	
	c. A/D Converters	
	d. Temperature Sensor Inputs	
	e. Pressure Sensor Inputs	
	f. Flow Sensor Inputs	
	g. Power Supply BIT Inputs	
2.	MultiBus II Interface	5
F.	**HIGH SPEED INPUT ELECTRONICS (HSIE):**	**TECH. READINESS LEVEL:**
1.	A/D Converters	5
2.	Capacitive Displacement Sensors	4
	a. Hydrogen TPA monitor	
	b. Oxygen TPA monitor	
	c. Hydrogen boost pump mon.	
	d. Oxygen boost pump monitor	
3.	Accelerometer Inputs	4
	a. Signal Processing	
4.	MultiBus II Interface	5
G.	**INTERCHANNEL COMMUNICATIONS (ICC):**	**TECH. READINESS LEVEL:**
1.	Input Select Control	4
2.	Data Registers	5
3.	Voting Circuit/Software	4
4.	MultiBus II Interface	5

Table VI (Cont.)

H. CONTROL SOFTWARE:	TECH. READINESS LEVEL:
1. Operating System	3
2. Executive Program	3
3. Vehicle I/F	3
4. Monitoring System I/F	3
5. Interchannel Communication	3
6. Power Up/Preflight Sequencer	3
7. Engine Start/Tank Head Idle	3
8. Pumped Idle	3
9. Main Stage/Throttling Thrust	3
10. Main Stage/Throttling MR	3
11. Shutdown/Post Flight Safing	3
12. Red-line/Emergency Shutdown	3
13. Fault Response Control (Library)	3
14. Built-In Test	3

I. DIAGNOSTIC MONITORING SOFTWARE:	TECH. READINESS LEVEL:
1. Operating System	2
2. Executive Program	2
3. Controller I/F	2
4. Interchannel Communication	2
5. Preflight Readiness Assessment	2
6. Safety Monitor/Red-line Assessment	2
7. Real Time Model	2
8. Sensor Data Validation	2
9. Sensor Failure ID	2
10. Parameter Est./Update IDR	2
11. Performance Validation	2
12. Performance Failure ID	2
13. Performance Fault Control Seq. ID	2
14. Component Health Validation	2
15. Component Failure ID	2
16. Component Fault Control Seq. ID	2
17. Post Flight Condition Assessment	2
18. ICHM Environment Monitoring	2
19. Built-In Test	2

J. POWER SUPPLY ELECTRONICS:	TECH. READINESS LEVEL:
1. Input Conditioning	5
2. Controller/Monitor Power Supply	5
3. ICHM Heater Power Supply	5
4. MultiBus II Interface	5

Table VI (Cont.)

K.	MASS DATA STORAGE:	TECH. READINESS LEVEL:
1.	Data Archive	4
2.	MultiBus II Interface	5

L.	HARNESSES:	TECH. READINESS LEVEL:
1.	Monitoring Sensor Harness (Control, Safety, and Condition)	7
2.	Solenoid Control Valve Power Harness	7
3.	Triple Channel 1553 Command and Data Bus	6

M.	DISTRIBUTED SIGNAL CONDITIONERS:	TECH. READINESS LEVEL:
1.	O_2 Leak Sensor	1
2.	H_2 Leak Sensor	2+
3.	Plume Anomaly Sensors	4
4.	H_2 TPA Displacement and Speed	4
5.	O_2 TPA Displacement and Speed	4
6.	H_2 Boost Pump Displacement and Speed	4
7.	O_2 Boost Pump Displacement and Speed	4

N.	CONTROL EFFECTORS:	TECH. READINESS LEVEL:
1.	HMSV H_2 Main Shutoff Valve	4
2.	OMSV O_2 Main Shutoff Valve	4
3.	HTBV H_2 Turbine Bypass Valve	4
4.	OTBV O_2 Turbine Bypass Valve	4
5.	HRBV H_2 Regenerator Bypass Valve	4
6.	HEBV HEX Bypass Valve	4
7.	HIV H_2 Idle Valve	4
8.	HPV H_2 Flow Proportioner Valve	4
9.	OTPV Ox Tank Pressurization Valve	5
10.	HTBV Fuel Tank Pressurization Valve	5
11.	HICV Igniter H_2 Control Valve	5
12.	OICV Igniter O_2 Control Valve	5
13.	IGN Igniter	5
14.	EN Extendable Nozzle	5
15.	GAP1 Gimbal Actuator, Pitch #1	5
16.	GAP2 Gimbal Actuator, Pitch #2	5
17.	GAY1 Gimbal Actuator, Yaw #1	5
18.	GAY2 Gimbal Actuator, Yaw #2	5

Table VI (Cont.)

19.	GAEO Gimbal Actuator, Engine Out			5

O.	SENSORS:			TECH. READINESS LEVEL:
1.	O2 TPA			
	a.	T08a	Pump Discharge Temperature	7
	b.	T08b	Pump Discharge Temperature	7
	c.	T09a	Turbine Inlet Temperature	7
	d.	T09b	Turbine Inlet Temperature	7
	e.	T10a	Turbine Discharge Temperature	7
	f.	T10b	Turbine Discharge Temperature	7
	g.	P08a	Pump Discharge Pressure	7
	h.	P08b	Pump Discharge Pressure	7
	i.	P10	Turbine Inlet Pressure	7
	j.	F04a	Pump Flowrate	4
	k.	F04b	Pump Flowrate	4
	l.	S05a	Pump Speed, 0	4
	m.	S05b	Pump Speed, 90	4
	n.	Z13a	Shaft Axial Displacement, 0	4
	o.	Z13b	Shaft Axial Displacement, 90	4
	p.	Z14	Shaft Radial Displacement, 0	4
	q.	Z16	Shaft Radial Displacement, 90	4
	r.	Z17a	TPA Vibration #1	7
	s.	Z17b	TPA Vibration #1	7
	t.	Z22a	O_2 Turbine Bypass Valve Position	7
	u.	Z22b	O_2 Turbine Bypass Valve Position	7
2.	O_2 Boost Pump			
	a.	T11	Inlet Temperature	7
	b.	P11	Inlet Pressure	7
	c.	S07	Speed	4
	d.	Z18	Bearing Outer Race Deflectometer	4
	e.	Z19	Bearing Outer Race Deflectometer	4
3.	H_2 TPA			
	a.	T01a	Pump Discharge Temperature	7
	b.	T01b	Pump Discharge Temperature	7
	c.	T04a	Turbine Inlet Temperature	7
	d.	T04b	Turbine Inlet Temperature	7
	e.	P01a	Pump Discharge Pressure	7
	f.	P01b	Pump Discharge Pressure	7
	g.	P05	Turbine Inlet Pressure	7
	h.	F01a	Flowrate #1	4
	i.	F01b	Flowrate #2	4
	j.	S01a	Pump Speed-1st Stage, 0	4
	k.	S01b	Pump Speed-1st Stage, 90	4

Table VI (Cont.)

	l.	S03a	Pump Speed-2nd Stage, 0	4
	m.	S03b	Pump Speed-2nd Stage, 90	4
	n.	Z01a	Shaft Axial Displ.-1st Stage, 0	4
	o.	Z01b	Shaft Axial Displ.-1st Stage, 90	4
	p.	Z02	Shaft Radial Displ.-1st Stage, 0	4
	q.	Z04	Shaft Radial Displ.-1st Stage, 90	4
	r.	Z06a	Shaft Axial Displ.-2nd Stage, 0	4
	s.	Z06b	Shaft Axial Displ.-2nd Stage, 90	4
	t.	Z07	Shaft Radial Displ.-2nd Stage, 0	4
	u.	Z09	Shaft Radial Displ.-2nd Stage, 90	4
	v.	Z05a	TPA Vibration #1	7
	w.	Z05b	TPA Vibration #1	7
	x.	Z21a	Turbine Bypass Valve	7
	y.	Z21b	Turbine Bypass Valve	7
4.	H_2 Boost Pump			
	a.	T07	Boost Pump Inlet Temperature	7
	b.	P07	Boost Pump Inlet Pressure	7
	c.	S06	Boost Pump Speed	4
	d.	Z10	Bearing Outer Race Deflect.	4
	e.	Z11	Bearing Outer Race Deflect.	4
5.	TCA			
	a.	T13	Injector H_2 Inlet Temperature	7
	b.	T14	Injector O_2 Inlet Temperature	7
	c.	T15	Chamber H_2 Coolant Outlet Temp.	7
	d.	T17	MCC Throat Temperature	7
	e.	T19	Nozzle O_2 Coolant Inlet Temp.	7
	f.	T23	Baffle H_2 Outlet Temperature	7
	g.	P12a	Chamber Pressure	7
	h.	P12b	Chamber Pressure	7
	i.	P13	Injector H_2 Inlet Pressure	7
	j.	P14	Injector O_2 Inlet Pressure	7
	k.	P15	Baffle H_2 Coolant Inlet Pressure	7
	l.	P17	Chamber H_2 Coolant Inlet Pressure	7
	m.	P18	Nozzle O_2 Coolant Inlet Pressure	7
	n.	HM1	Plume Spectral Emission Analyzer	4
6.	HEX			
	a.	Z23a	HEX Bypass Valve Position	7
	b.	Z23b	HEX Bypass Valve Position	7
7.	H2 Regenerator			
	a.	T21	Regen. H_2 Outlet Temperature	7
	b.	P02	Regen. H_2 Inlet Pressure	7
	c.	Z25a	Regen. Bypass Valve Position #1	7
	d.	Z25b	Regen. Bypass Valve Position #2	7
8.	Nozzle Extension			
	a.	L09	Nozzle Position	7
	b.	L10	Nozzle Position	7

Table VI (Cont.)

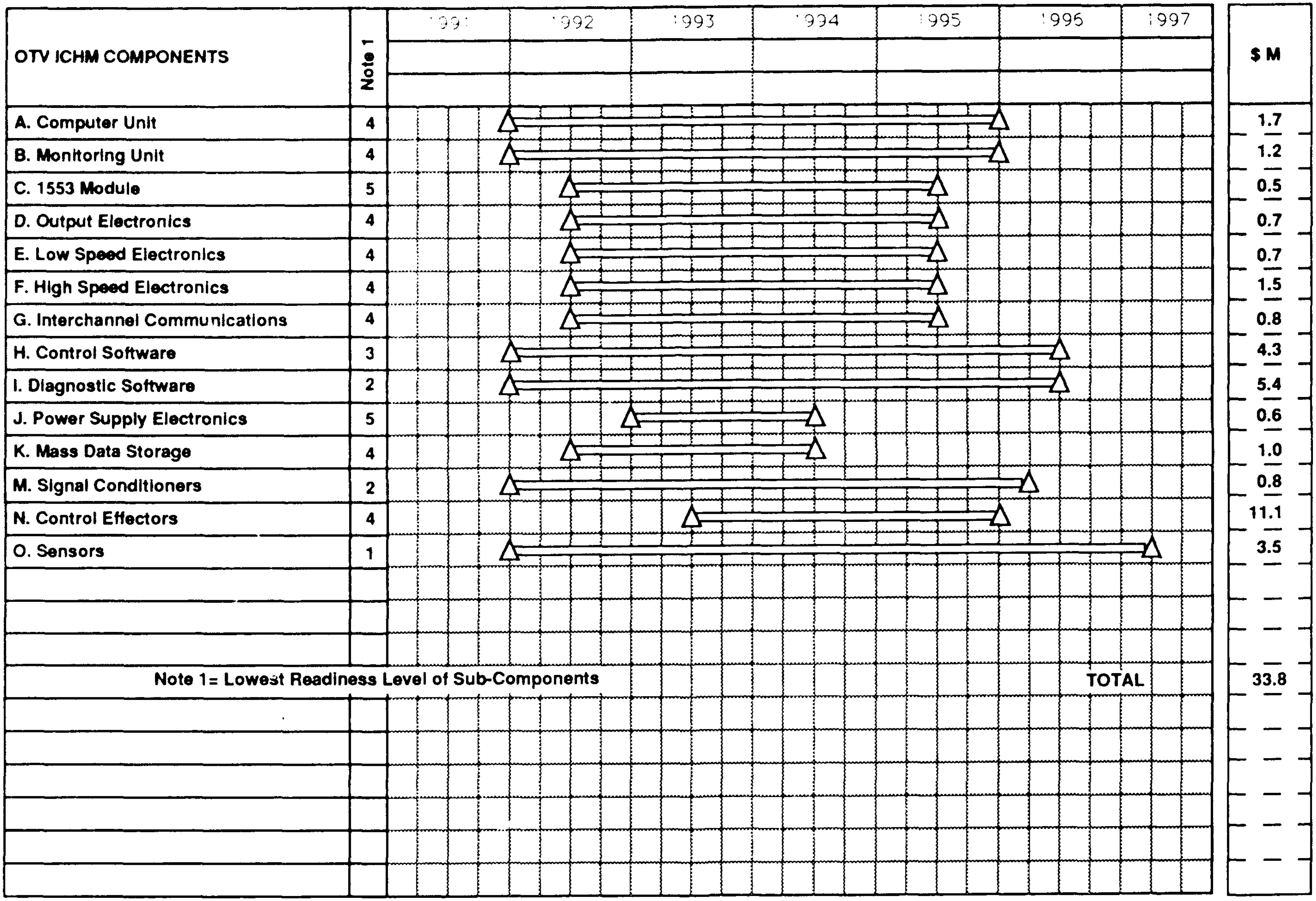
	c.	L11	Nozzle Position	7
	d.	L12	Nozzle Position	7
	e.	L13	Nozzle Position	7
	f.	L14	Nozzle Position	7
	g.	L15	Nozzle Latch Position	7
	h.	L16	Nozzle Latch Position	7
	i.	I01	Actuator Motor Current Draw	4
	j.	I02	Actuator Motor Current Draw	4
	k.	T28	Ball Screw Bearing #1 Temp.	7
	l.	T29	Ball Screw Bearing #2 Temp.	7
	m.	T30	Ball Screw Bearing #3 Temp.	7
9.	Gimbal Actuator			
	a.	Z27a	Pitch #1 Actuator Position	7
	b.	Z27b	Pitch #2 Actuator Position	7
	c.	Z30a	Yaw #1 Actuator Position	7
	d.	Z30b	Yaw #2 Actuator Position	7
	e.	I04	Actuator Motor Current Draw	4
	f.	I05	Actuator Motor Current Draw	4
10.	O_2 Feed/Tank			
	a.	P11	O_2 Tank Inlet Pressure	7
	b.	Z29	Main O_2 Valve Position	7
	c.	L05	O_2 Tank Press. Valve Position	7
	d.	L06	O_2 Tank Press. Valve Position	7
11.	H_2 Feed/Tank			
	a.	P07	H_2 Tank Inlet Pressure	7
	b.	Z28	Main H_2 Valve Position	7
	c.	L07	H_2 Tank Press. Valve Position	7
	d.	L08	H_2 Tank Press. Valve Position	7
12.	Igniter			
	a.	L01	Igniter H_2 Valve Position	7
	b.	L02	Igniter H_2 Valve Position	7
	c.	L03	Igniter O_2 Valve Position	7
	d.	L04	Igniter O_2 Valve Position	7
	e.	I06	Igniter Spark Current	4
13.	Engine Compartment			
	a.	T24	Engine Compartment Temperature	7
	b.	T25	Engine Compartment Temperature	7
	c.	T26	Engine Compartment Temperature	7
	d.	T27	Engine Compartment Temperature	7
	e.	HM2	H_2 Propellant Leak Sensor	2+
	f.	HM3	O_2 Propellant Leak Sensor	1
14.	Idle Valve			
	a.	Z24a	H_2 Idle Valve Position	7
	b.	Z24b	H_2 Idle Valve Position	7
15.	Proportioner Valve			
	a.	Z31a	H_2 Proportioner Valve Position	7
	b.	Z31b	H_2 Proportioner Valve Position	7

6.0 REMAINING DEVELOPMENT COST FOR MINIMAL SYSTEM

The cost and schedule necessary to advance the elements of the minimum required ICHM system to readiness level 6 were estimated. A summary of these estimates is presented in Figure 12. This figure shows the current readiness level of each of the system elements required for minimum ICHM, as well as the estimated cost and schedule required to develop each of the elements to readiness level 6. The complete effort is estimated to cost $33.8M, and require approximately five years.

The cost and schedule estimates prepared were focused on generic requirements for an effective space based engine ICHM system. Although some details are specific to the Aerojet 7,500-lbF dual expander cycle OTV, the technology roadmap that results is applicable to any advanced space engine design as well as to upgrading existing upper stage systems for space basing. One such advanced space engine currently in development is the Advanced Expander Test Bed (AETB), currently scheduled for delivery in 1996. This test bed engine could provide a suitable environment for system level validation of the advanced ICHM described in this report.

A brief summary of the status for each element and the associated tasks of advancing the technology to level 6 are described in Table VII. These cost and schedule estimates were based on analysis of the ICHM system development requirements by teams of experts at Aerojet Propulsion Division in Sacramento, California. Each element was evaluated by three to five team members having appropriate expertise and experience with the technologies considered. Principal contributors were Gordon Spear (Manager, Controls and Instrumentation Design Engineering), Ed Reich (Manager, Control Systems Analysis), Gary Patterson (Project Engineer, ALS Engine Controller ADP), Matt Lister (Project Engineer, ALS Propellant Effectors ADP), Lee Bickford (Project Engineer, Space Shuttle OMS), Deena Morgan (Project Engineer, OTV and Space Engine Technology), Frank Collamore (Project Engineer, OTV Advanced Control and Monitoring Technology), Mark Gage (Lead Project Engineer, Advanced Control and Monitoring Technology), Erv Thomas (Control Systems Design), and Randy Bickford (Manager, Advanced Control and Monitoring Programs). Other specialists provided input as required.



otvc_s

Figure 12. OTV Schedule to Bring ICHM Components to Tech Readiness Level 6

TABLE VII

DEVELOPMENT COST OF OTV ICHM SYSTEM

ICHM ELEMENT: Computer Unit

ELEMENT NO: A., B.

DESCRIPTION: Utilized for the control and monitoring of the engine system that includes verification of sensor data, engine effector control, redline determination and interface management.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The present breadboard level hardware design requires testing in a relevant environment. Based on the results of the testing, the breadboard design must be refined to create a system validation model that subsequently must be demonstrated in a simulated environment in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $2.4M

ESTIMATED SCHEDULE: 48 Months

Task	1990	1991	1992	1993	1994	1995	1996
Breadboard Testing							
Design Update							
Hardware Fabrication							
Demonstration Testing							

TABLE VII (Cont)

ICHM ELEMENT: Controller Housing

ELEMENT NO: A.3.

DESCRIPTION: Provide hardware backplane and environmental protection for card modular engine controller and power supply electronics.

CURRENT TECHNOLOGY READINESS LEVEL: 5

REQUIRED DEVELOPMENT: System specific hardware design, fabrication and test for integration into a system validation model controller that subsequently must be demonstrated in simulated environments in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $500K

ESTIMATED SCHEDULE: 36 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update			——				
Hardware Fabrication				——			
Acceptance Testing					——		
Demonstration Testing					——		

TABLE VII (Cont)

ICHM ELEMENT: Triple Channel 1553B Module

ELEMENT NO: C.1. thru C.4.

DESCRIPTION: The vehicle, telemetry, and control effector interface are achieved using the 1553B module.

CURRENT TECHNOLOGY READINESS LEVEL: 5

REQUIRED DEVELOPMENT: The present breadboard level hardware design must be refined to create a system validation model that subsequently must be demonstrated in simulated environments to advance this technology to Readiness Level 6.

ESTIMATED COST: $500K

ESTIMATED SCHEDULE: 36 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update			———				
Hardware Fabrication				———			
Demonstration Testing					———		

TABLE VII (Cont)

ICHM ELEMENT: General Output Electronics (GOE)

ELEMENT NO: D.1. thru D.6.

DESCRIPTION: Provides driver signals for activating solenoid valves and igniters and accepts valve position and igniter feedback signals.

CURRENT TECHNOLOGY READINESS LEVEL: D.1. and D.2. are Level 4, while D.3. thru D.6. are Level 5.

REQUIRED DEVELOPMENT: The breadboard level hardware design must be refined to create a system validation model that subsequently must be demonstrated in simulated environments to advance this technology to Readiness Level 6.

ESTIMATED COST: $700K

ESTIMATED SCHEDULE: 36 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update							
Hardware Fabrication							
Demonstration Testing							

TABLE VII (Cont)

ICHM ELEMENT: Low Speed Input Electronics (LSIE)

ELEMENT NO: E.1. thru E.2.

DESCRIPTION: Provides precision voltage references and built-in test features for software programmable instrumentation channels.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The breadboard level hardware design must be refined to create a system validation model that subsequently must be demonstrated in simulated environments in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $700K

ESTIMATED SCHEDULE: 36 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update							
Hardware Fabrication							
Demonstration Testing							

TABLE VII (Cont)

ICHM ELEMENT: High Speed Input Electronics (HSIE)

ELEMENT NO: F.1. thru F.4.

DESCRIPTION: Provide digital signal processing for higher frequency signals such as accelerometers and capacitive displacement transducers.

CURRENT TECHNOLOGY READINESS LEVEL: F.1. and F.4. are Level 5, while F.2. and F.3. are Level 4.

REQUIRED DEVELOPMENT: The breadboard level hardware design must be refined to create a system validation model that subsequently must be demonstrated in simulated environments in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $1.5M

ESTIMATED SCHEDULE: 36 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update			———				
Hardware Fabrication				———			
Demonstration Testing					———		

TABLE VII (Cont)

ICHM ELEMENT: Interchannel Communications (ICC)

ELEMENT NO: G.1. thru G.4.

DESCRIPTION: Provides for data exchange and transaction voting between the three redundant controller channel input and output parameters.

CURRENT TECHNOLOGY READINESS LEVEL: G.1. and G.3. are Level 4, while G.2. and G.4. are Level 5.

REQUIRED DEVELOPMENT: The breadboard level hardware design must be refined to create a system validation model that subsequently must be demonstrated in simulated environments in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $800K

ESTIMATED SCHEDULE: 36 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update			—	—			
Hardware Fabrication				—	—		
Demonstration Testing					—	—	

TABLE VII (Cont)

ICHM ELEMENT: Control Software

ELEMENT NO: H.1. thru H.14.

DESCRIPTION: The complex control requirements for the engine requires a software library within the control computer unit that incorporates portable Ada procedural code plus a UNIX based operating system.

CURRENT TECHNOLOGY READINESS LEVEL: 3

REQUIRED DEVELOPMENT: Develop breadboard level software for incorporation in the breadboard level computer unit and conduct development testing in a relevant environment. Based on the results of this testing, plus evaluation using a real time engine model on an AD 100 or equivalent computer, the software design could be refined for inclusion within the system validation model of the computer unit. This version of the control software will then be evaluated during computer unit demonstration testing in order to advance this software technology to Readiness Level 6.

ESTIMATED COST: $4.3M

ESTIMATED SCHEDULE: 54 Months

Task	1990	1991	1992	1993	1994	1995	1996
Software Development							
Real Time Engine Model (AD 100)							
Breadboard Evaluation							
Software Update							
AETB Demonstration Evaluation							

TABLE VII (Cont)

ICHM ELEMENT: Diagnostic Monitoring Software

ELEMENT NO: I.1. thru I.19.

DESCRIPTION: The complex monitoring requirements for the engine requires a software library within the monitoring computer that incorporates portable Ada procedural code plus expert system capability for diagnostic function.

CURRENT TECHNOLOGY READINESS LEVEL: 2

REQUIRED DEVELOPMENT: Develop breadboard level software for incorporation in the breadboard level computer unit and conduct development testing in a relevant environment. Based on the results of this testing, plus evaluation using a real time engine model on an AD 100 or equivalent computer, the software design could be refined for inclusion within the system validation model of the computer unit. This version of the diagnostic monitoring software will then be evaluated during computer unit demonstration testing in order to advance this software technology to Readiness Level 6.

ESTIMATED COST: $5.4M

ESTIMATED SCHEDULE: 54 Months

Task	1990	1991	1992	1993	1994	1995	1996
Software Development							
Breadboard Evaluation							
Software Update							
AETB Demonstration Testing							

TABLE VII (Cont)

ICHM ELEMENT: Power Supply Electronics

ELEMENT NO: J.1. thru J.3.

DESCRIPTION: Provides filtered and regulated power for all ICHM systems and includes failure sensing plus an interrupt in order to preserve controller memory in the event of an input power failure.

CURRENT TECHNOLOGY READINESS LEVEL: 5

REQUIRED DEVELOPMENT: The breadboard level hardware design must be refined to create a system validation model that subsequently must be demonstrated in simulated environments in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $600K

ESTIMATED SCHEDULE: 18 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update				—			
Hardware Fabrication				—	—		
Demonstration Testing					—		

TABLE VII (Cont)

ICHM ELEMENT: Mass Data Storage

ELEMENT NO: K.1. thru K.2.

DESCRIPTION: Provides for mass data storage of engine parameters by writing this data to an optical disk.

CURRENT TECHNOLOGY READINESS LEVEL: K.1. is Level 4 and K.2. is Level 5.

REQUIRED DEVELOPMENT: The breadboard level hardware design must be refined to create a system validation model that subsequently must be demonstrated in simulated environments in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $1.0M

ESTIMATED SCHEDULE: 24 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update			—	—			
Hardware Fabrication				—			
Demonstration Testing					—		

TABLE VII (Cont)

ICHM ELEMENT: O_2 Leak Sensor and Distributed Signal Conditioner

ELEMENT NO: M.1. and O.13.f.

DESCRIPTION: The sensor provides the capability to sense oxygen propellant leakage within the engine compartment, especially in the region of flanges and welds. The signal conditioner is a self-contained package which communicates with the control unit via the MIL-STD-1553B bus and performs data processing of the leak sensor signals.

CURRENT TECHNOLOGY READINESS LEVEL: 1

REQUIRED DEVELOPMENT: Conceptual design development will precede proof-of-concept fabrication and laboratory testing. This will be followed by the fabrication of a breadboard sensor system design with subsequent testing in a relevant environment. Finally, the design will be updated to a system validation model package for fabrication and demonstration in order to advance the technology to Readiness Level 6.

ESTIMATED COST: Conceptual design and proof-of-concept testing, $125K. Breadboard system design, fabrication and test, $550K. System validation design, fabrication and test on AETB, $200K. Total estimated cost is $875K.

ESTIMATED SCHEDULE: 63 Months

Task	1990	1991	1992	1993	1994	1995	1996
Conceptual Design							
Conceptual Design Fabrication							
Proof-of-Concept Testing							
Breadboard Design							
Breadboard Fabrication							
Breadboard Testing							
AETB Design Update							
Hardware Fabrication							
AETB Demonstration Testing							

TABLE VII (Cont)

ICHM ELEMENT: H_2 Leak Sensor and Distributed Signal Conditioner

ELEMENT NO: M.2. and O.13.e.

DESCRIPTION: The sensor provides the capability to sense hydrogen propellant leakage within the engine compartment, especially in the region of flanges and welds. The signal conditioner is a self-contained package which communicates with the control unit via the MIL-STD-1553B bus and performs data processing of the leak sensor signals.

CURRENT TECHNOLOGY READINESS LEVEL: 2+

REQUIRED DEVELOPMENT: Conceptual design development will precede proof-of-concept fabrication and laboratory testing. This will be followed by the fabrication of a breadboard sensor system design with subsequent testing in a relevant environment. Finally, the design will be updated to a system validation model package for fabrication and demonstration in order to advance the technology to Readiness Level 6.

ESTIMATED COST: Laboratory and breadboard system design, fabrication and test, $500K. System validation design, fabrication, and test, $200K. Total estimated cost is $700K.

ESTIMATED SCHEDULE: 63 Months

Task	1990	1991	1992	1993	1994	1995	1996	1997
Conceptual Design								
Conceptual Design Fabrication								
Proof-of-Concept Testing								
Breadboard Design								
Breadboard Fabrication								
Breadboard Testing								
AETB Design Update								
Hardware Fabrication								
AETB Demonstration Testing								

TABLE VII (Cont)

ICHM ELEMENT: Fabry-Perot Interferometric Spectrometer (Optical Plume Monitor) and Distributed Signal Conditioner

ELEMENT NO: M.3. and O.5.n.

DESCRIPTION: The spectrometer provides the capability to sense anomalous materials contained within the engine exhaust plume that would be indicative of component failure, material erosion, or wear. Presently in development under NAS 3-25624. The signal conditioner is a self-contained package which communicates with the control unit via the MIL-STD-1553 bus and performs data processing of the plume sensor signals.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The existing laboratory breadboard instrument design must be hardened and tested in a relevant environment. Based on the results of this testing, the breadboard design must be refined to create a 12 channel system validation model instrument that subsequently must be demonstrated in simulated environments, including altitude engine tests, in order to advance this technology to Readiness Level 6.

ESTIMATED COST: Test stand breadboard, $360K. Twelve channel flight prototype instrument development, $640K. System validation testing on AETB, $100K. Total estimated cost $1.1M.

ESTIMATED SCHEDULE: 54 Months

Task	1990	1991	1992	1993	1994	1995	1996
Laboratory Testing			—				
AETB Breadboard Testing				—			
Flight Prototype Design				—	—		
Flight Prototype Hardware					—	—	
AETB Demonstration Testing						—	—

TABLE VII (Cont)

ICHM ELEMENT: Capacitive Displacement Sensor and Distributed Signal Conditioner

ELEMENT NO: M.4. thru M.7., O.1.1. thru O.1.q., O.2.C. thru O.2.e., O.3.j. thru O.3.u., and O.4.c. thru O.4.e.

DESCRIPTION: The sensors provide a measurement of pump speed, shaft axial and radial displacement, and bearing race deflection. In the minimal system, the signal conditioner with the oscillator plus amplification are in close proximity to the sensor and linearization plus digitization takes place in the controller HSIE.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The present breadboard level hardware design requires some fabrication effort prior to testing in a relevent environment. Based on the results of this testing, the breadboard must be refined to create a system validation model components for demonstration in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $250K for breadboard activity followed by $500K for design update, fabrication and demonstration testing. Total estimated cost $750K.

ESTIMATED SCHEDULE: 30 Months

Task	1990	1991	1992	1993	1994	1995	1996
Breadboard Fabrication					—		
Breadboard Testing					—		
Design Update						—	
Hardware Fabrication						—	
AETB Demonstration Testing							—

TABLE VII (Cont)

ICHM ELEMENT: Main Shutoff Valve Control Effector (HCV, OCV)

ELEMENT NO: N.1. thru N.2.

DESCRIPTION: These control effectors are electromechanical actuator driven ball valves which are connected to the MIL-STD-1553 bus. The electromechanical actuators use brushless DC motors with integral driver electronics. This is a common valve for HCV and OCV.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The common valve/actuator design used for HCV and OCV will be based upon the results of the ALS breadboard level testing. This breadboard design could be refined to create system validation model components for fabrication and demonstration in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $1.5M

ESTIMATED SCHEDULE: 21 Months

Task	1990	1991	1992	1993	1994	1995	1996
ALS Breadboard Testing				—			
Final Detail Design					—		
Hardware Fabrication					—		
AETB Demonstration Testing						—	

TABLE VII (Cont)

ICHM ELEMENT: Bypass Valve Control Effector (HRBV, HIV, HPT)

ELEMENT NO: N.3., N.4., and N.6.

DESCRIPTION: These control effectors are electromechanical linear actuator drive hot gas bypass pintle valves which are connected to the MIL-STD-1553 bus. The electromechanical actuators use brushless DC motors with integral driver electronics. This is a common design for the HTBV, OTBV, and HEBV.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The electronics and motor design will be based on the ALS breadboard design. The AETB breadboard level hardware will require an update of the gearing and pintle valve design. Fabrication and testing in a relevant environment will follow. Based on the results of this testing, the breadboard design must be refined to create system validation model components for fabrication and demonstration on the AETB in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $0.5M for breadboard activities plus $2.0M for design update, fabrication, and AETB demonstration testing. Total estimate is $2.5M.

ESTIMATED SCHEDULE: 33 Months

Task	1990	1991	1992	1993	1994	1995	1996
Breadboard Design							
Breadboard Fabrication							
Breadboard Testing							
Final Detail Design							
Hardware Fabrication							
AETB Demonstration Testing							

TABLE VII (Cont)

ICHM ELEMENT: Bypass/Idle/Flow Proportioner Valve Control Effector (HRBV, HIV, HPV)

ELEMENT NO: N.5., N.7., N.8.

DESCRIPTION: These control effectors are electromechanical actuator driven pintle valves which are connected to the MIL-STD-1553 bus. The electromechanical actuators use brushless DC motors with integral driver electronics. This is a common design for the HRBV, HIV, and HPV.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The electronics and motor design will be based on the ALS breadboard design. The AETB breadboard level hardware will require an update of the gearing and pintle valve design. Fabrication and testing in a relevant environment will follow. Based on the results of this testing, the breadboard design must be refined to create system validation model components for fabrication and demonstration on the AETB in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $0.5M for breadboard activities plus $2.0M for design update, fabrication, and AETB demonstration testing. Total estimate is $2.5M.

ESTIMATED SCHEDULE: 33 Months

Task	1990	1991	1992	1993	1994	1995	1996
Breadboard Design							
Breadboard Fabrication							
Breadboard Testing							
Final Detail Design							
Hardware Fabrication							
AETB Demonstration Testing							

TABLE VII (Cont)

ICHM ELEMENT: Tank Pressurization and Igniter Control Valve Control Effector (OTPV, HTBV, HICV, OICV)

ELEMENT NO: N.9. thru N.12.

DESCRIPTION: These control effectors are solenoid operated poppet valves whose drivers are located within the engine controller output electronics.

CURRENT TECHNOLOGY READINESS LEVEL: 5

REQUIRED DEVELOPMENT: The breadboard level hardware design will be refined to create a system validation model of components for fabrication and demonstration on the AETB in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $300K

ESTIMATED SCHEDULE: 15 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update				—			
Hardware Fabrication					—		
AETB Demonstration Testing					—		

TABLE VII (Cont)

ICHM ELEMENT: Igniter Control Effector (IGN)

ELEMENT NO: N.13.

DESCRIPTION: This igniter is used to initiate the engine combustion and is electrically connected to drivers within the engine controller output electronics.

CURRENT TECHNOLOGY READINESS LEVEL: 5

REQUIRED DEVELOPMENT: The breadboard level hardware design will be refined to create a system validation model of components for fabrication and demonstration on the AETB in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $300K

ESTIMATED SCHEDULE: 15 Months

Task	1990	1991	1992	1993	1994	1995	1996
Design Update					——		
Hardware Fabrication					——		
AETB Demonstration Testing					——		

TABLE VII (Cont)

ICHM ELEMENT: Extendable Nozzle Control Effector (EN)

ELEMENT NO: N.14.

DESCRIPTION: This control effector is an electromechanical device consisting of a brushless DC motor driving a ball screw acltuator which is controlled through the MIL-STD-1553 bus. This effector is used to extend and retract the radiation cooled nozzle.

CURRENT TECHNOLOGY READINESS LEVEL: 5

REQUIRED DEVELOPMENT: The electronics and motor design will be based on the ALS breadboard design. The breadboard hardware design will be refined to include the proper gear transmission for AETB testing. The system validation model components must be fabricated and subsequently demonstrated on the AETB in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $1.5M

ESTIMATED SCHEDULE: 21 Months

Task	1990	1991	1992	1993	1994	1995	1996
Final Detail Design				—			
Hardware Fabrication					—		
AETB Demonstration Testing					—		

TABLE VII (Cont)

ICHM ELEMENT: Gimbal Actuator Control Effector (GAP1, GAP2, GAY1, GAY2, GAEO)

ELEMENT NO: N.15. thru N.19.

DESCRIPTION: These control effectors are electromechanical linear devices consisting of a brushless DC motor driving a jack screw linear actuator, which is used to gimbal the engine and thus achieve thrust vector control.

CURRENT TECHNOLOGY READINESS LEVEL: 5

REQUIRED DEVELOPMENT: The electronics and motor design will be based on the ALS breadboard design. The breadboard level hardware will be refined to include AETB specific mechanical elements and thus create system validation model components for fabrication and demonstration on the AETB in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $2.5M

ESTIMATED SCHEDULE: 24 Months

Task	1990	1991	1992	1993	1994	1995	1996
Final Detail Design				—			
Hardware Fabrication					—		
AETB Demonstration Testing						—	

TABLE VII (Cont)

ICHM ELEMENT: Ultrasonic Flowmeter

ELEMENT NO: O.1.j., O.1.k., O.3.h., and O.3.i.

DESCRIPTION: Required for measuring the engine propellant flowrates.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The present breadboard level hardware designs have been tested using LN_2 to simulate LOX. Laboratory testing using cryogenic propellants is needed. Based on the results of this testing, the breadboard design must be refined and a validation model component built and tested in order to advance this technology to Readiness Level 6.

ESTIMATED COST: Build and test laboratory units with cryogenic LOX and LH_2, \$200K. Focused technology component design, fabrication and test on the AETB, \$350K. Total estimated cost is \$550K.

ESTIMATED SCHEDULE: 36 Months

Task	1990	1991	1992	1993	1994	1995	1996
Breadboard Testing			—				
AETB Design				—			
Hardware Fabrication				—	—		
AETB Demonstration Testing					—	—	

TABLE VII (Cont)

ICHM ELEMENT: Current Sensor

ELEMENT NO: O.8.i., O.8.j., O.9.e., O.9.f., O.12.e.

DESCRIPTION: Provide a measurement of the electrical current supplied to the igniter and the electromechanical actuators.

CURRENT TECHNOLOGY READINESS LEVEL: 4

REQUIRED DEVELOPMENT: The breadboard level hardware design for sensing current using power MOSFET transisters requires testing in a relevant environment. Based on the results of this testing, the breadboard level hardware design must be refined to create system validation model components that subsequently must be demonstrated in order to advance this technology to Readiness Level 6.

ESTIMATED COST: $300K

ESTIMATED SCHEDULE: 18 Months

Task	1990	1991	1992	1993	1994	1995	1996
Breadboard Testing					—		
Design Update					—		
Hardware Fabrication						—	
AETB Demonstration Testing						—	

Disparities in individual estimates of cost and schedule were resolved within the working groups through interactive evaluation of assumptions and issues. Although some estimates remained contentious, the groups arrived at most probable compromise values in each case. Uncertainties in cost and schedule are estimated at approximately +/-15% of the totals.

The study results show that a majority of the technologies required to develop a comprehensive ICHM system for a space based engine are accessible. The cost estimates presented assume that all technology development activity will occur concurrently within an integrated program activity focused on system development and demonstration by 1996. A fragmented development activity or extended schedule would invalidate this assumption.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The components of an Integrated Control and Health Monitoring system for the 7500 lbF OTV were defined and described. Many of the elements of the recommended ICHM system are currently in development. Most have been demonstrated at technology readiness Level 4 or above.

Many of the least technically mature components are under development on technology or engine development programs other than the OTV, such as the ALS Advanced Development Programs. Currently, the elements of the full ICHM receiving the most emphasis are the electronic hardware components. However, this study has shown the least mature elements are software for real time control and engine diagnostics and new sensors capable of providing important diagnostic measurements, such as propellant leak detectors. It is recommended that the estimates for remaining development costs and schedule contained in this study be reviewed and considered when prioritizing resources for ICHM development programs.

The individual, currently active development programs provide the basis to realize a complete ICHM system for future engines. The results of these individual programs should be integrated together to provide an effective and comprehensive ICHM system, such as the one described in this report.

8.0 REFERENCES

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